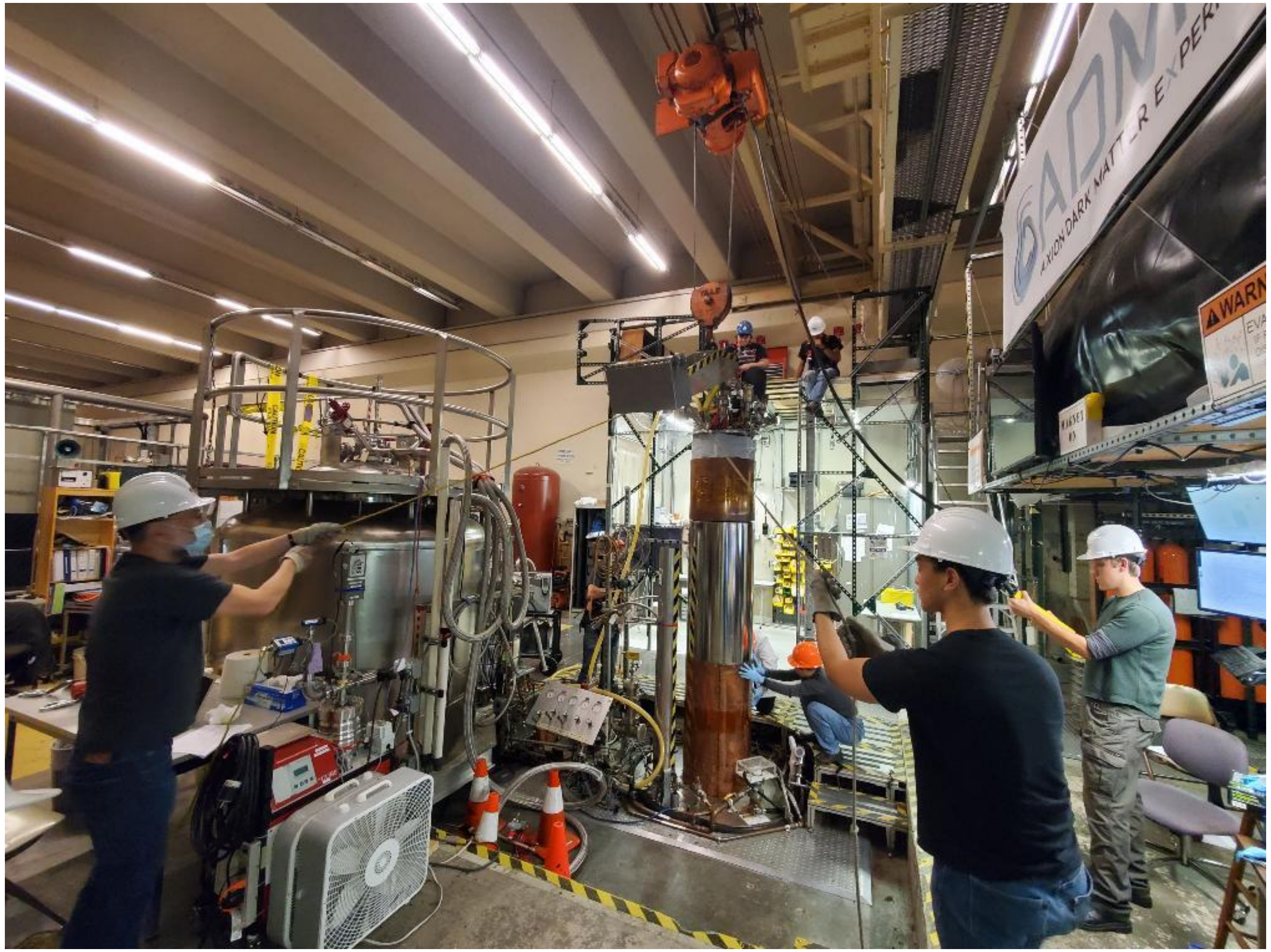
The Axion Dark Matter Experiment (ADMX)

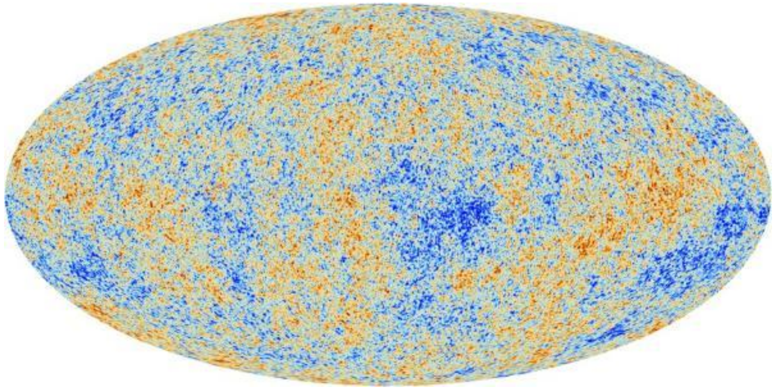


Gray Rybka – University of Washington

IBS Conference on the Dark World

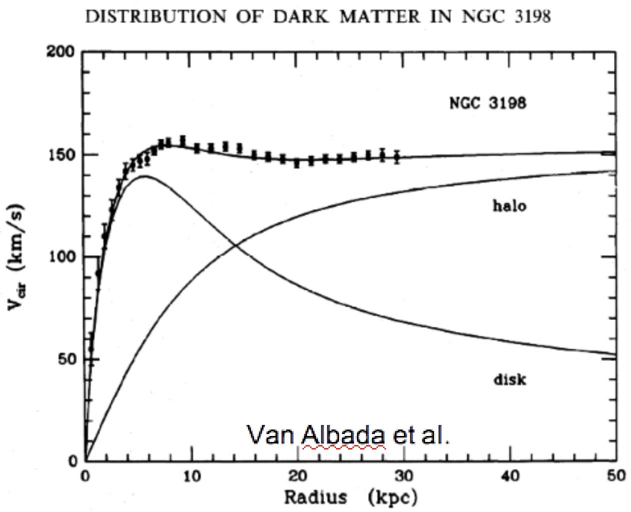
Daejeon – 27-10-2025

Evidence for Dark Matter



PLANCK CMB 2013 (ESA)

Our Hubble Volume



Nearby Galaxies

Composite: NASA, Markevitch etal., Clowe et al.

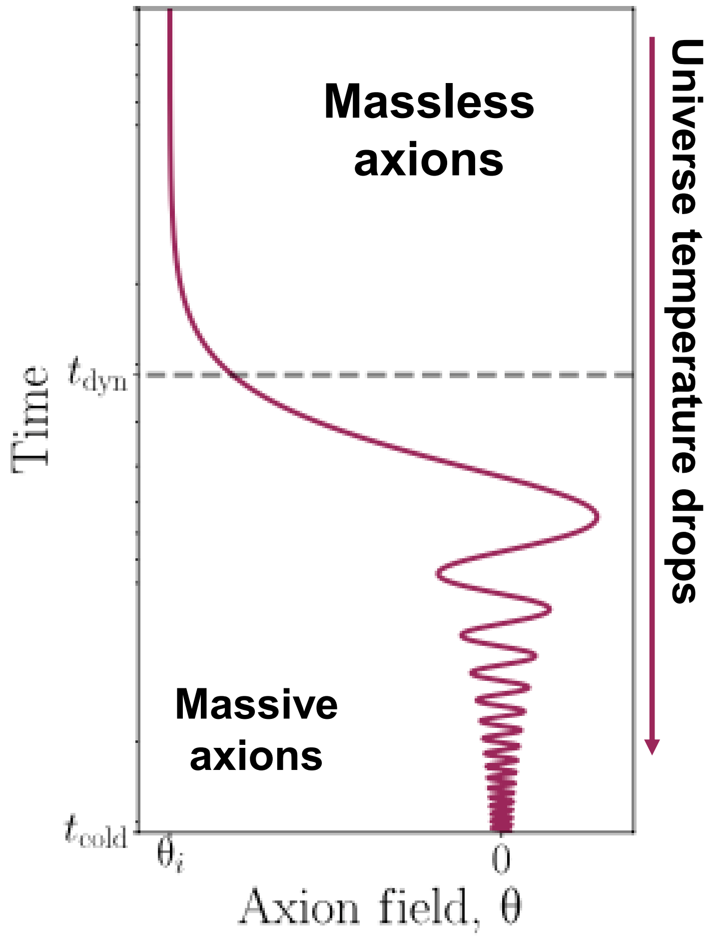
Galaxy Clusters

?

The Laboratory

Axions as Dark Matter

- Axions are produced athermally
  - Misalignment Mechanism – Phase transition in the early universe leaves energy in the axion field which behaves as dark matter
  - String/Defect Decay – Energy in topological defects radiates as cold axions
- In both cases axions are produced cold and in quantities sufficient to make up some or all of dark matter
- Perfect knowledge of QCD, cosmology, and inflation could, in principle, predict the axion mass that yields the amount of dark matter we have today



Francesca Chadha-Day, John Ellis, David J. E. Marsh, sciadv.abj3618

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

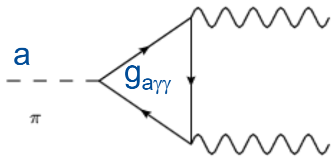
Coupling to Axial Nuclear Moment

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

Coupling to Nucleon EDM

Coupling to Axial Nuclear Moment

Coupling to Axial Electron Moment

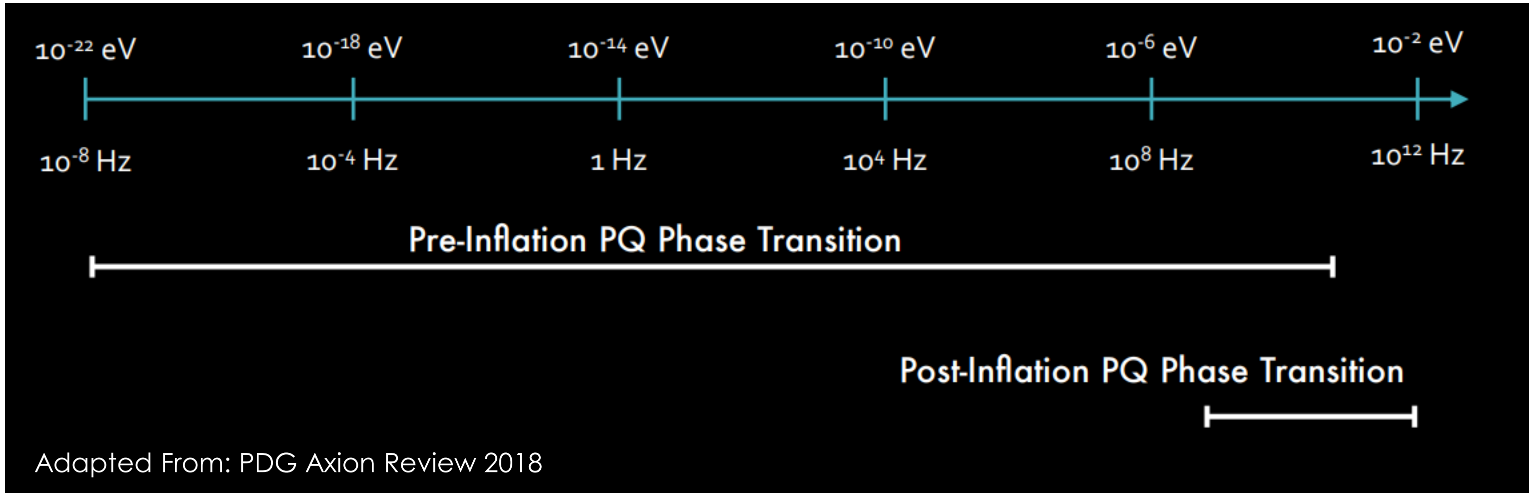
Clean experimental signal
Well developed techniques
Ripe for incorporating quantum sensing techniques

Promising experimental techniques under development

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

Theoretical Preferences on Scale

- 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



- Above 1 micro-eV, axions may have been produced after inflation

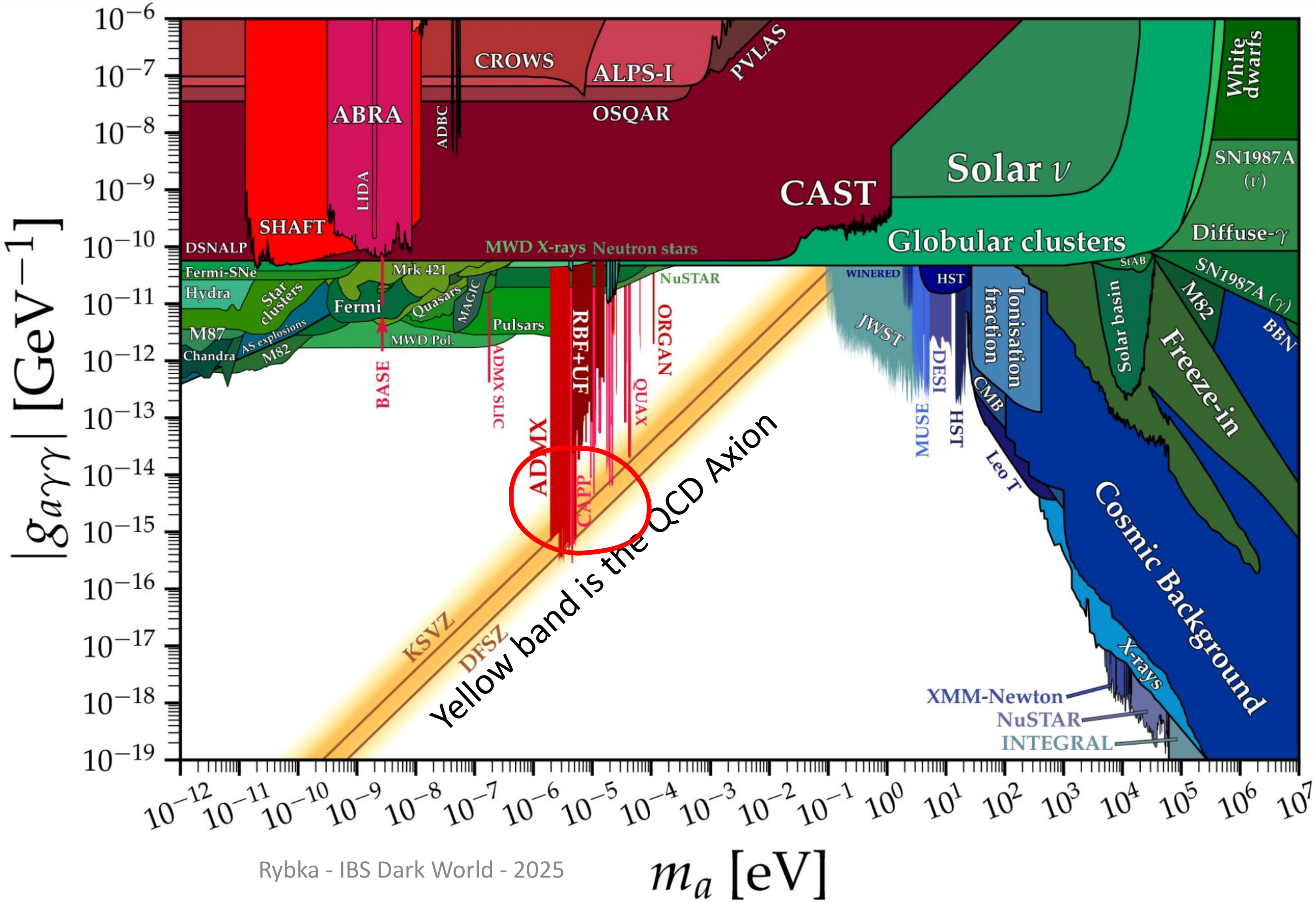
Axion Target Region

GitHub - cajohare/AxionLimits: Data, plots and code for constraints on axions, axion-like particles, and dark photons - includes zoom-in later on, updated Oct 2025

The yellow band is the QCD axion, white space is Axion-Like Particle (ALP) space

Note the significant astrophysical constraints on ALP parameters.

ADMX Targets a region where the QCD axion could make up some or all of the dark matter in our universe



Maxwell's Equations with an Axion Field

The Axion-Photon coupling can be interpreted classically as a small perturbation to Maxwell's equations:

$$\nabla \cdot E = \rho - g_{a\gamma\gamma} B \cdot \nabla a$$

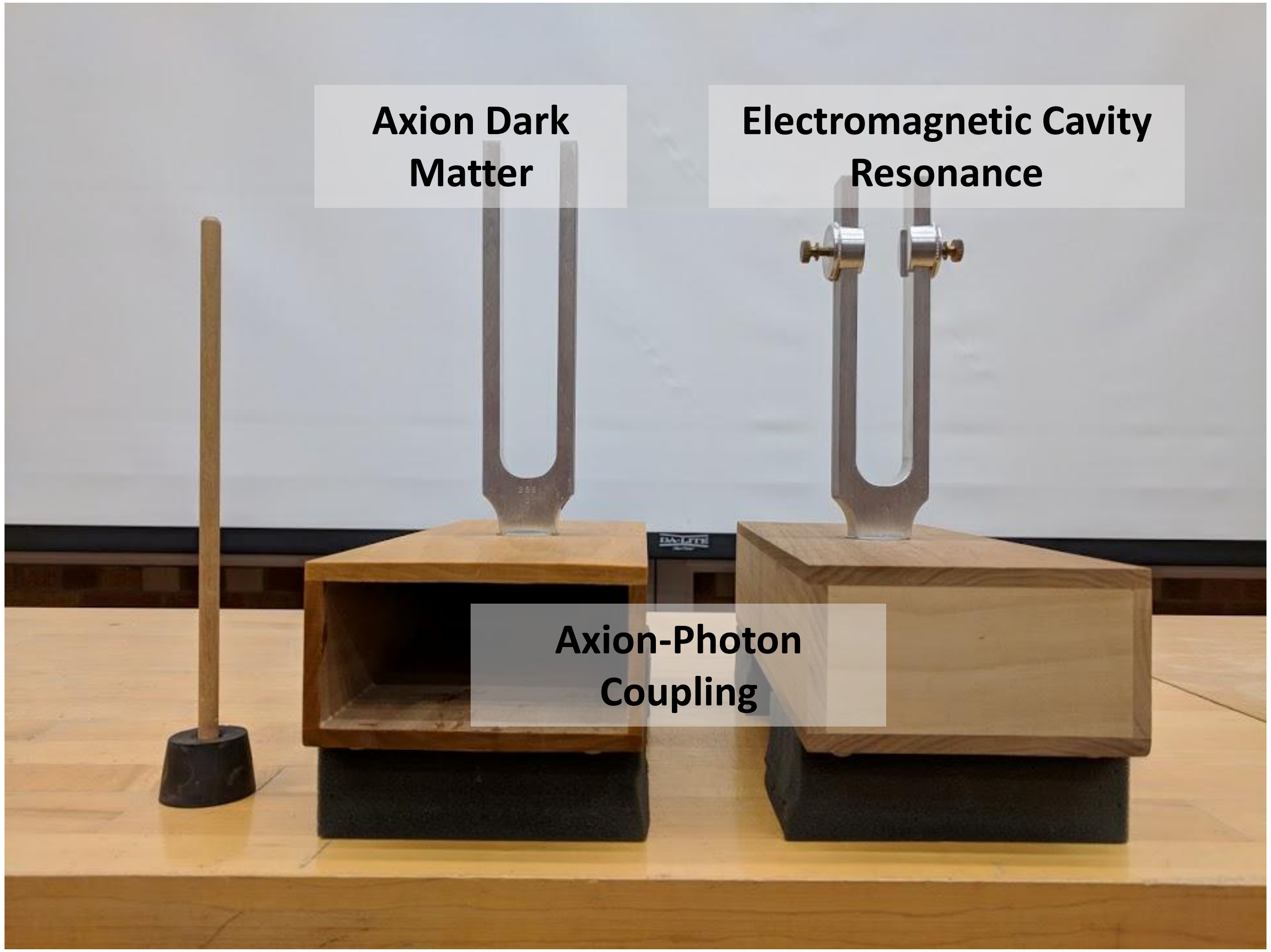
$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times B = \frac{\partial E}{\partial t} + J - g_{a\gamma\gamma}(\mathrm{E} \times \nabla a - B\frac{\partial a}{\partial t})$$

$$\nabla \cdot B = 0$$

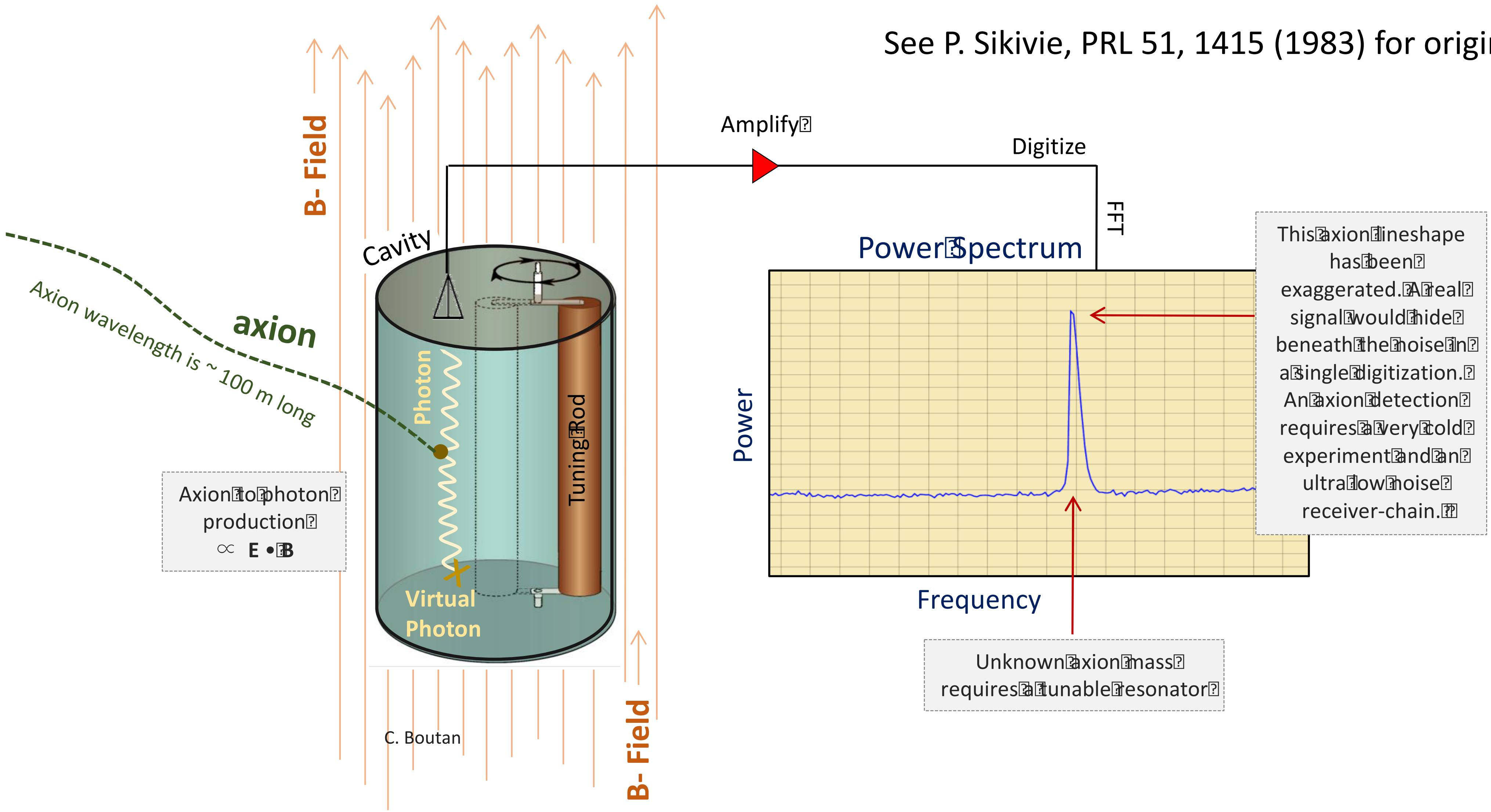
In particular, an axion field in a strong magnetic field radiates photons like a very weakly coupled antenna!

Axion Haloscope for my Intro Physics Class

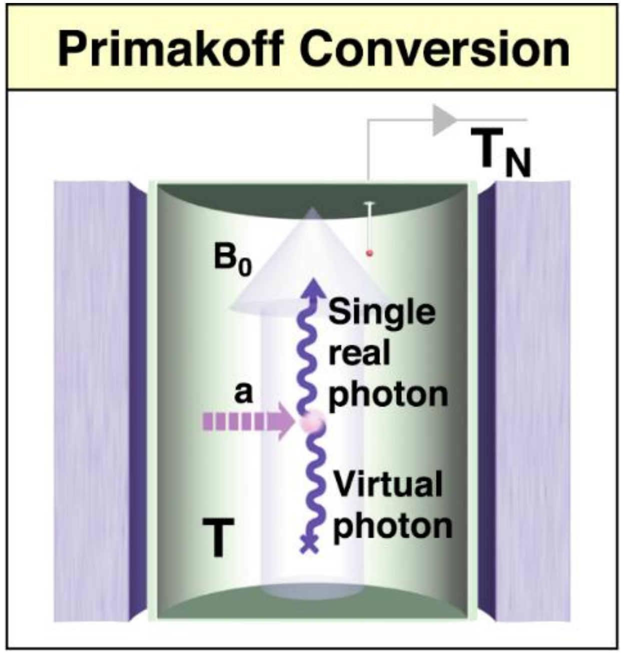


Principle of the Sikivie Axion Haloscope

See P. Sikivie, PRL 51, 1415 (1983) for origin



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

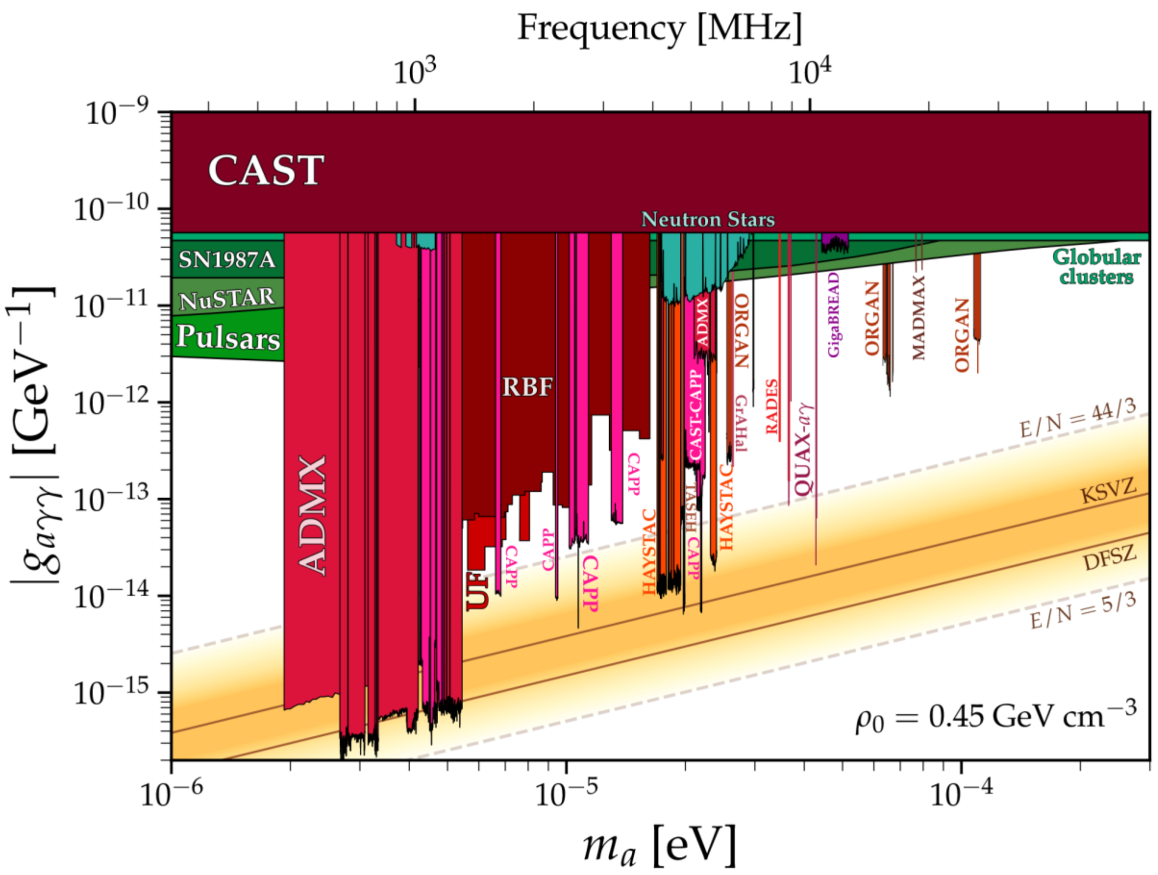
Cavity Q

Noise Proportional to

Cavity Blackbody Radiation

Amplifier Noise

The World of Axion Haloscopes



- A number of axion haloscopes are now operating worldwide. ADMX is aiming to find DFSZ axions at nominal dark matter densities

ADMX Collaboration

ADMX Collaboration meeting – UW - Jan 2023

Collaborating Institutions:

University of Washington
Washington University St. Louis
University of Western Australia
University of Florida
University of Sheffield
University of Western Australia
Stanford University / SLAC
UC Berkeley
Fermilab
Pacific Northwest National Laboratory
Lawrence Livermore National Laboratory
Los Alamos National Laboratory

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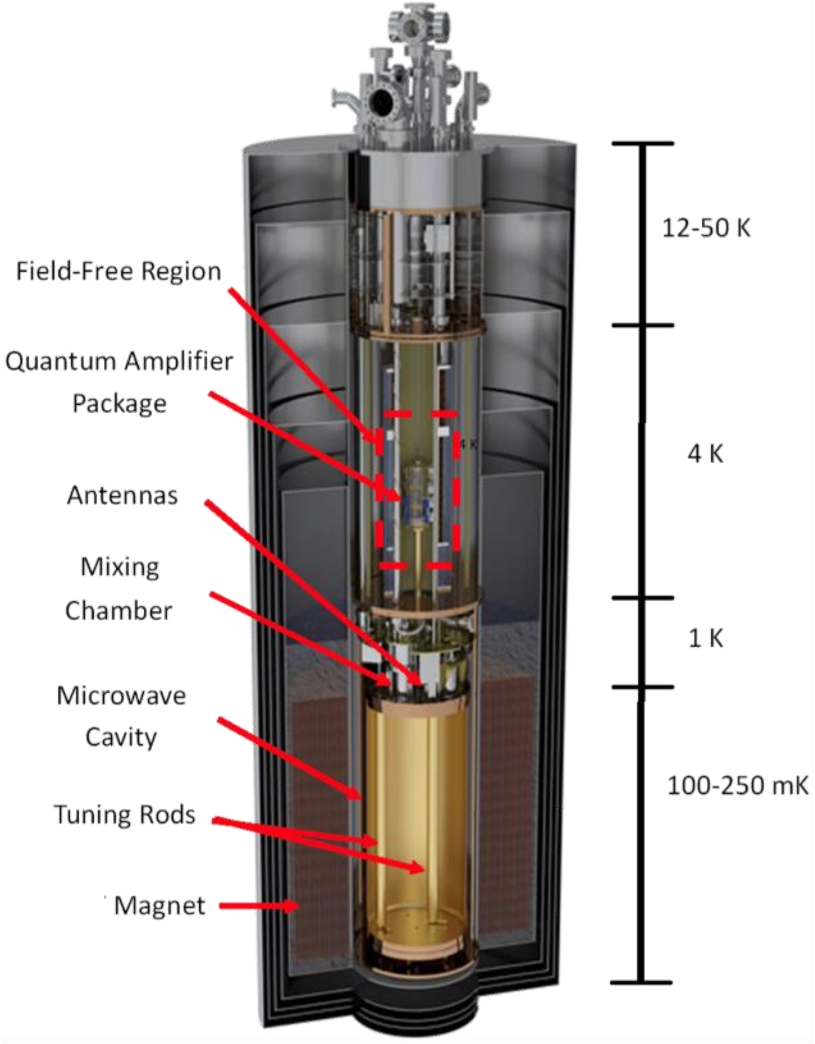
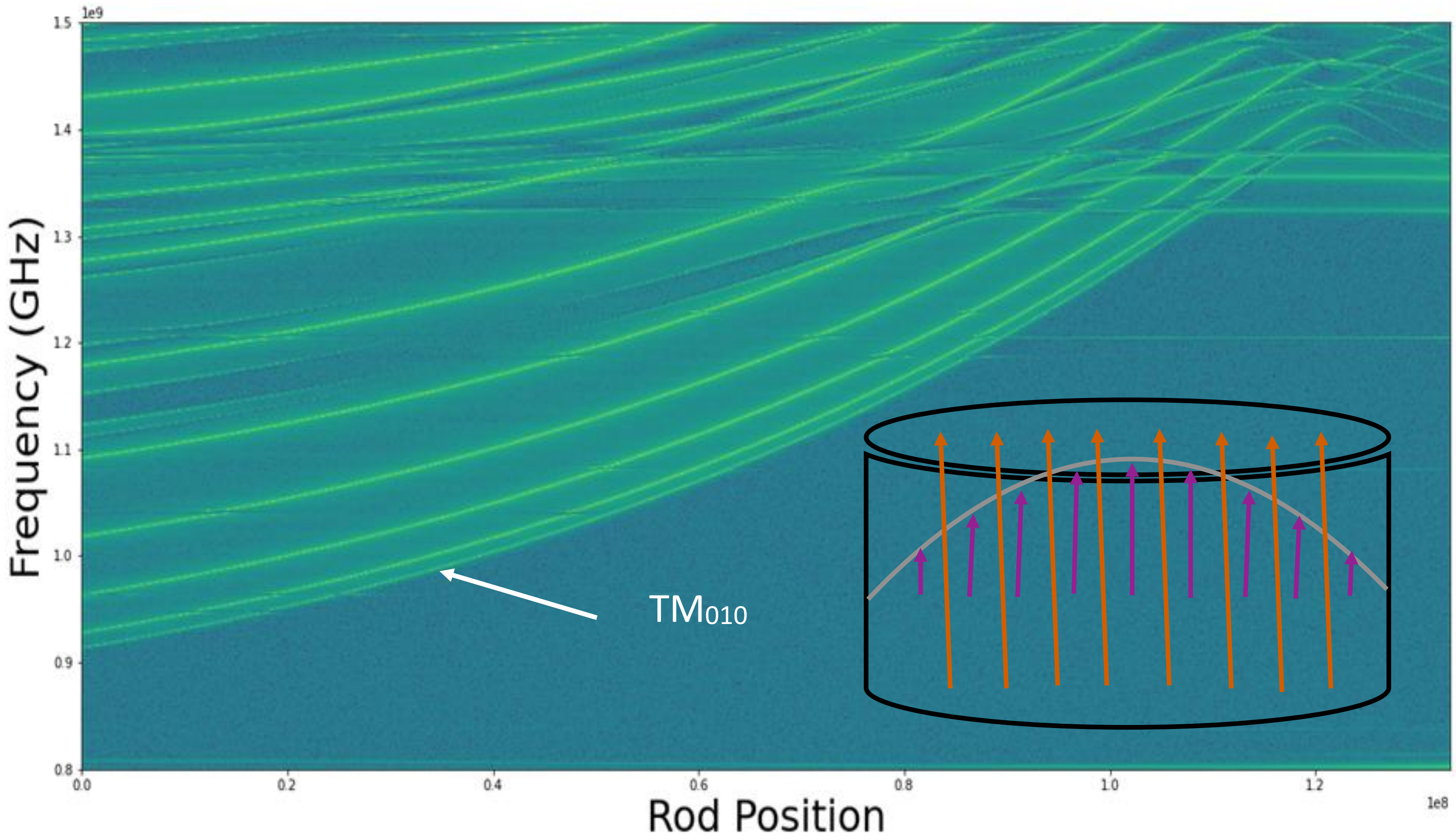
ADMX Design



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

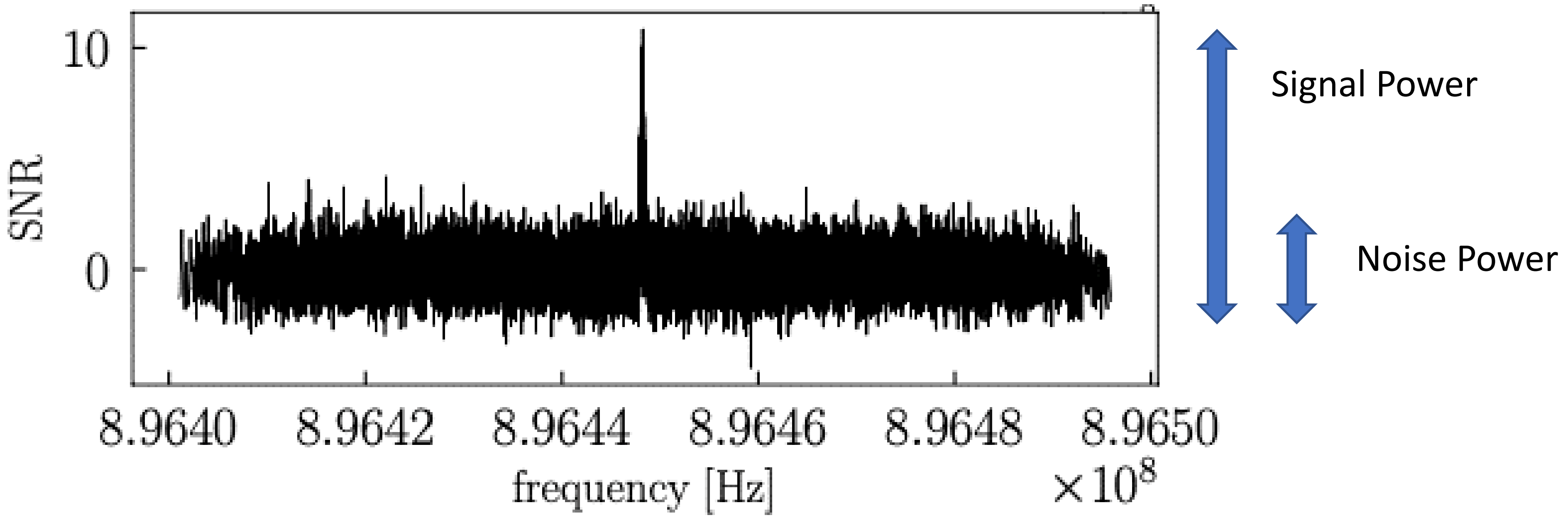
Tuning the Cavity Resonance



Run 1D

- We mechanically tune the resonator to scan over frequency space

The Importance of Noise

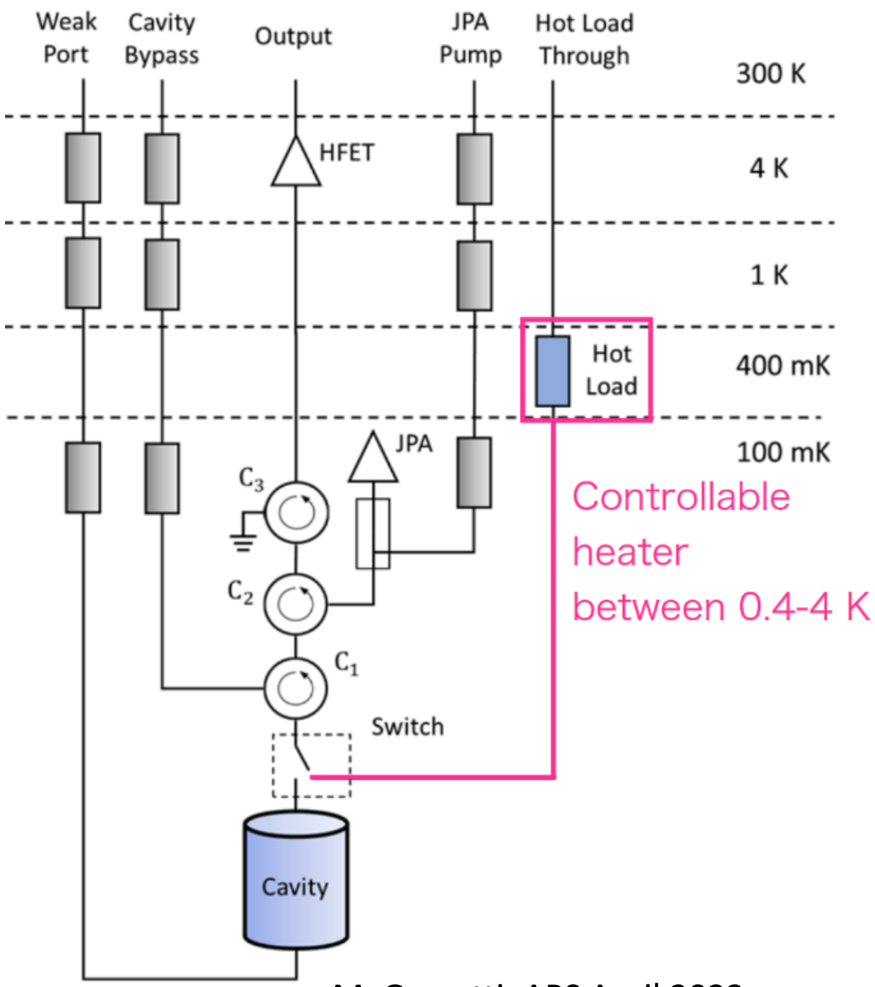


We need our noise to be much smaller than our signal to make a detection.

The noise is a thermal, and the slower we scan the smaller the uncertainty.

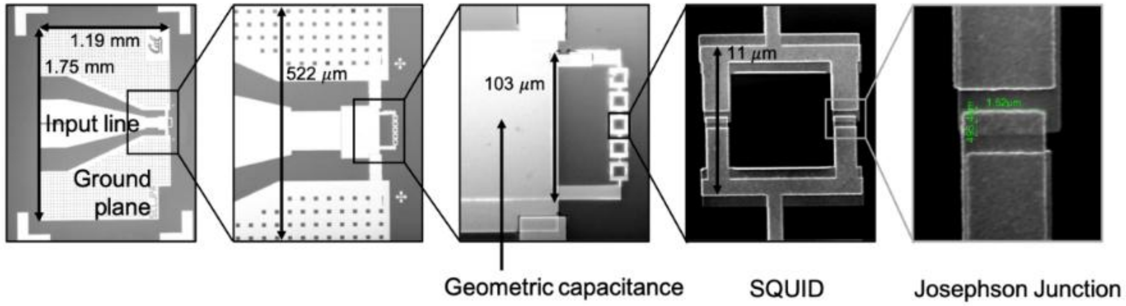
We must carefully calibrate the noise of our system – to understand our sensitivity, we must understand the temperatures of the components, the signal loss in the cables, and the performance of the amplifiers.

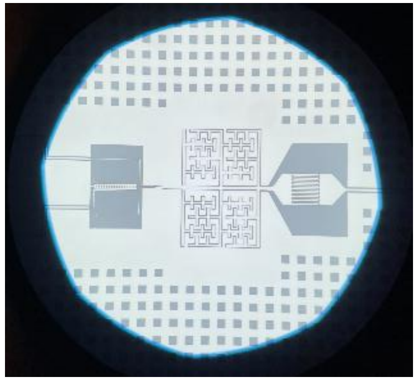
Minimizing Noise



M. Guzzetti, APS April 2023

Noise is minimized by cooling to millikelvin temperatures and using superconducting amplifiers operating at or near the standard quantum limit

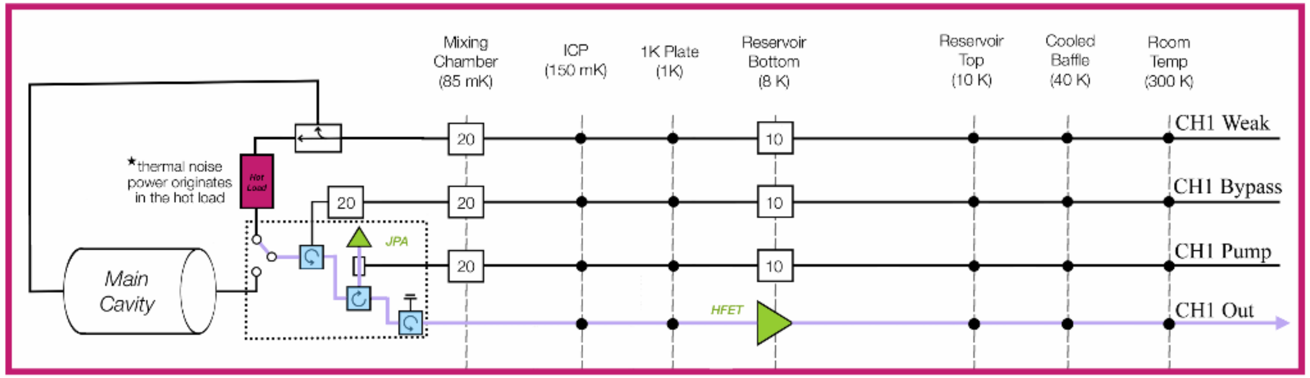


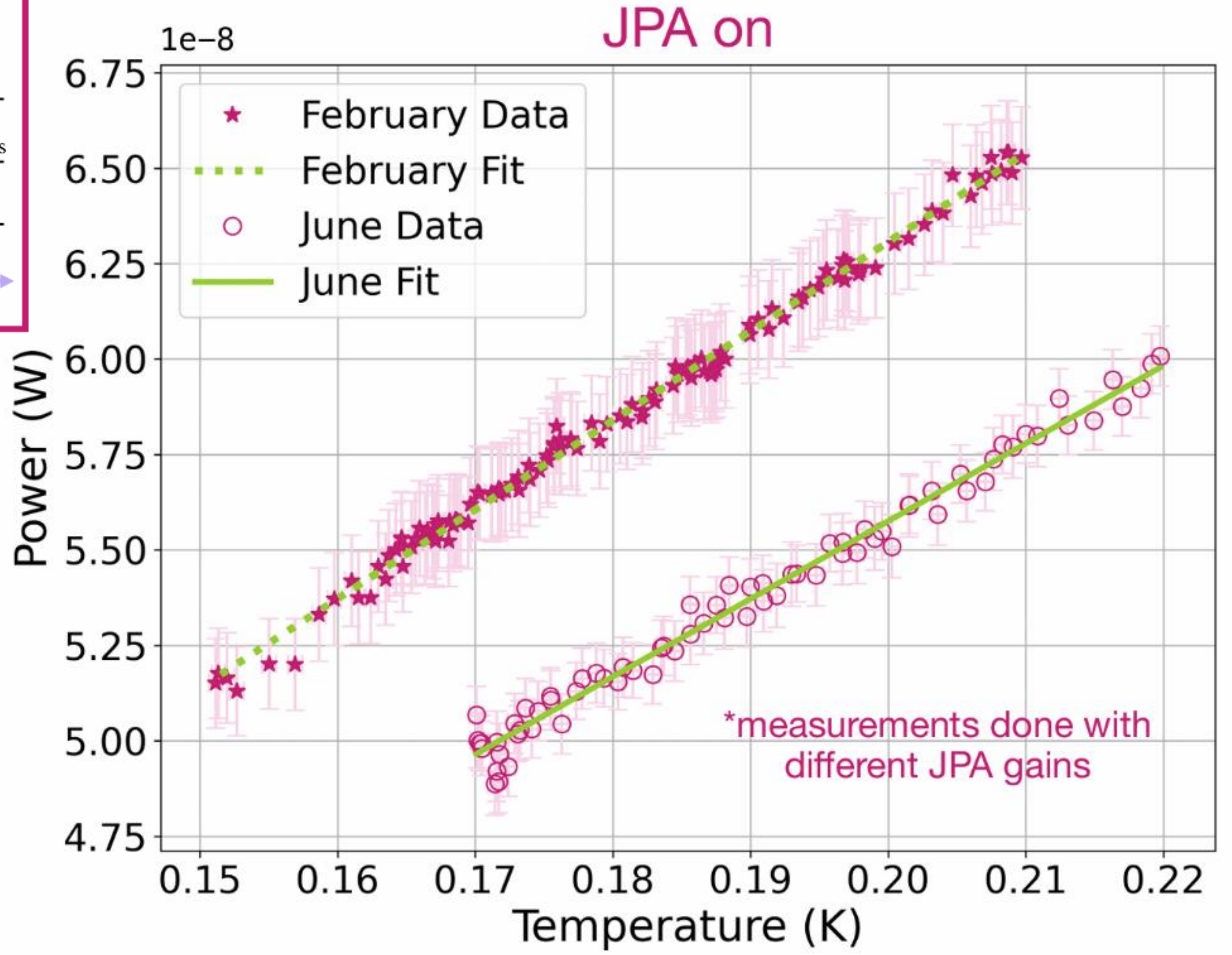


JPA provided by
Siddiq Group at UC Berkeley (previous run)
Wash. U. St. Louis (upcoming run)

TWPAs Under Test from Lincoln labs, JPL

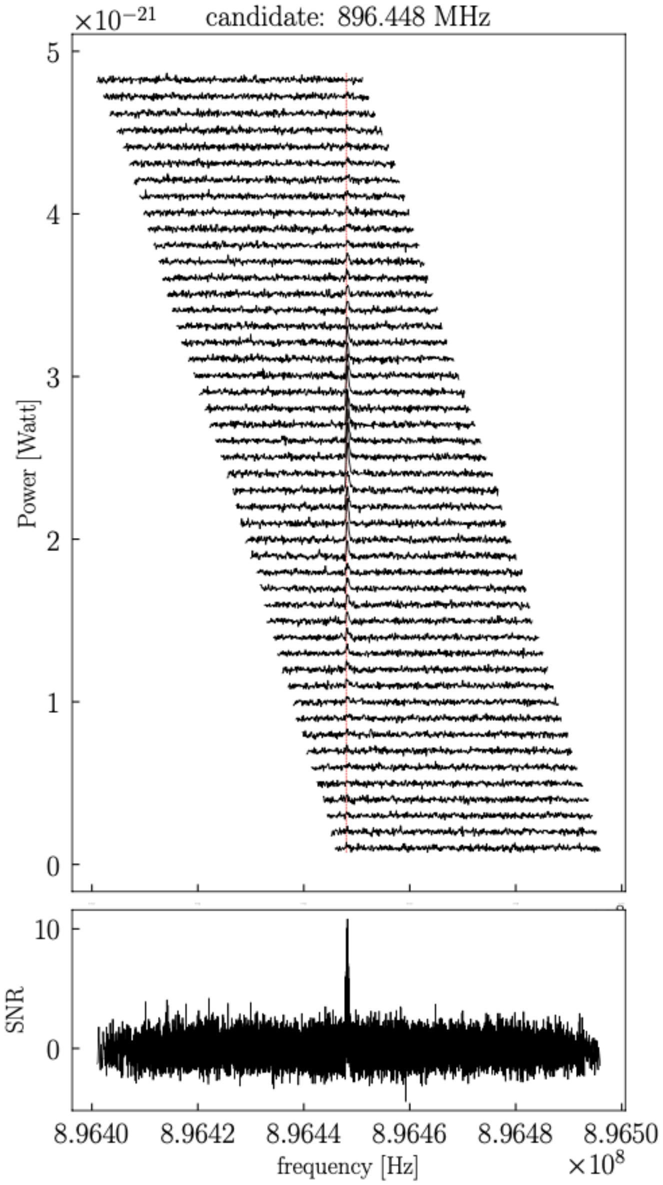
Noise Calibration





- Our primary noise calibration maps power directly to the temperature of a heated blackbody
- See M. Guzzetti et al. (Phys. Rev. D, 111, 092012 2025) for more details

ADMX Operations

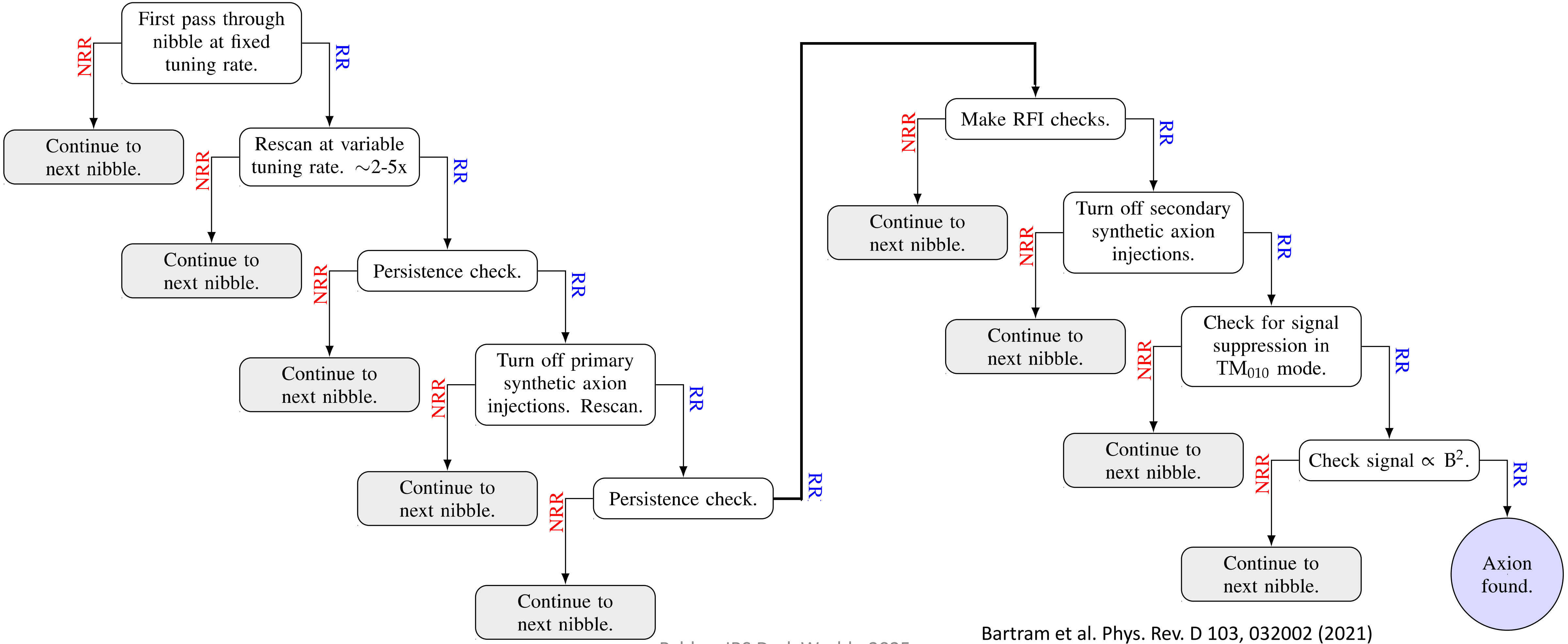


The cavity is tuned every 100 seconds, during which power spectra are taken. Overlapping power spectra are examined for the characteristic axion signal shape appearing on-resonance.

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

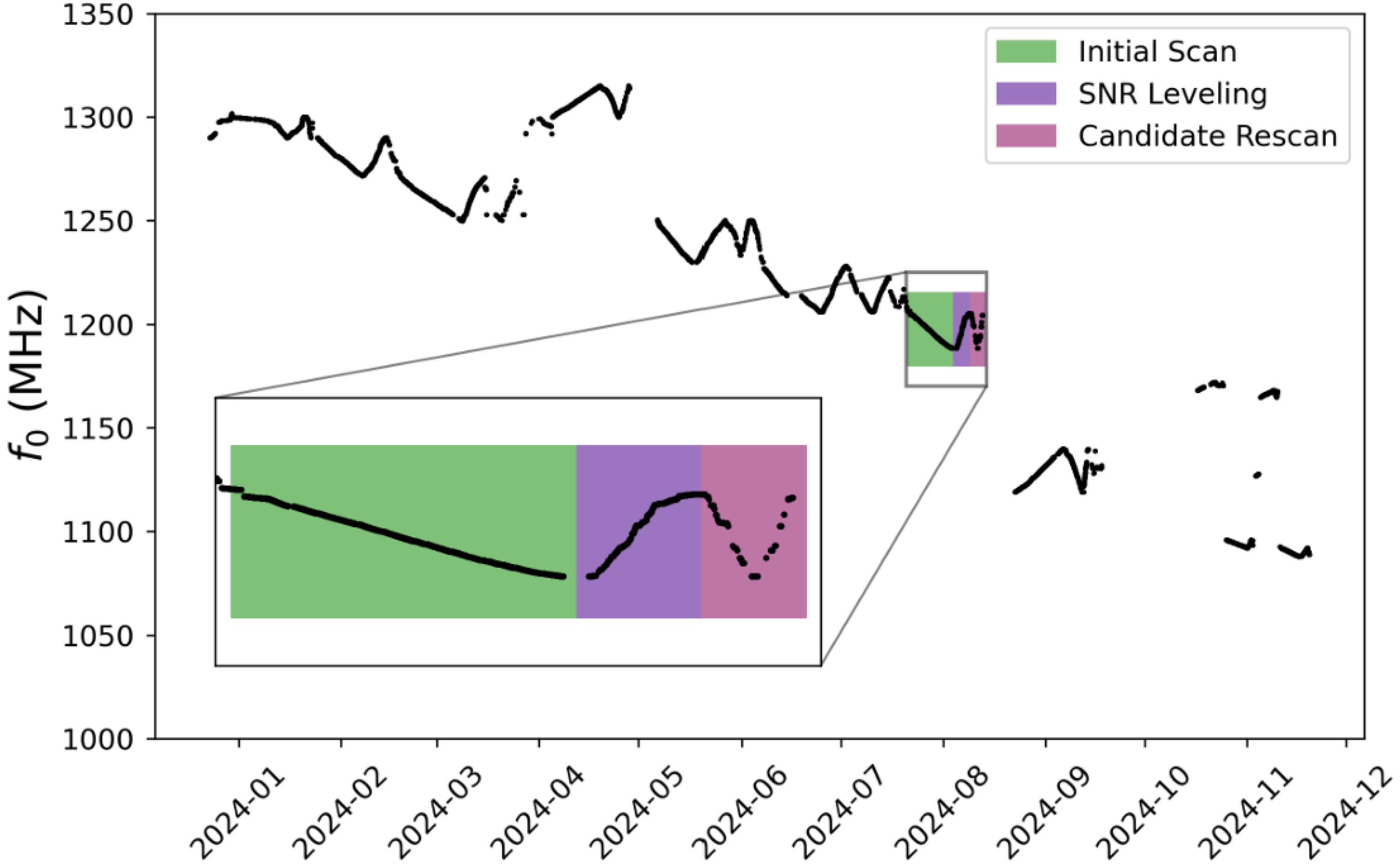
Data Taking Cadence

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



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

Example: ADMX 2024 Operations



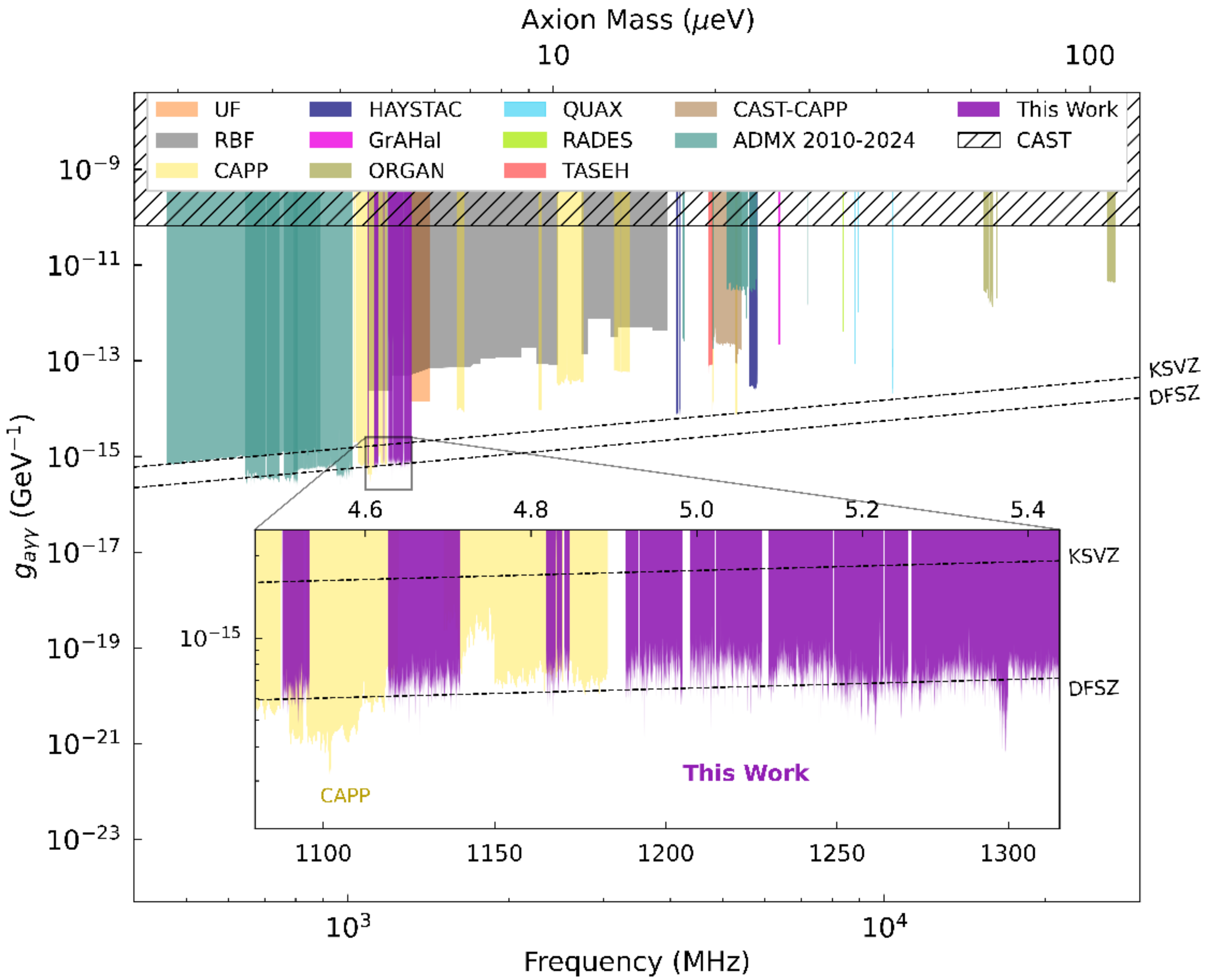
M. Guzzetti, Ph.D. Thesis 2025

2024 Results

Over the range explored:

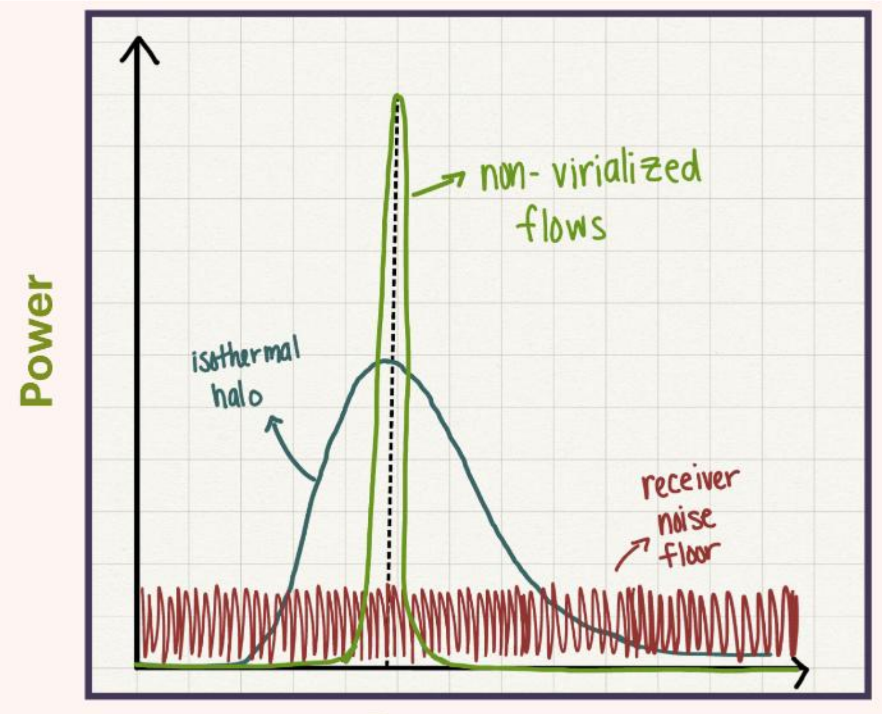
KSVZ Axion Model at nominal dark matter density excluded at 90% confidence between 1 GHz and 1.3 GHz

DFSZ Axion Model at slightly higher densities excluded



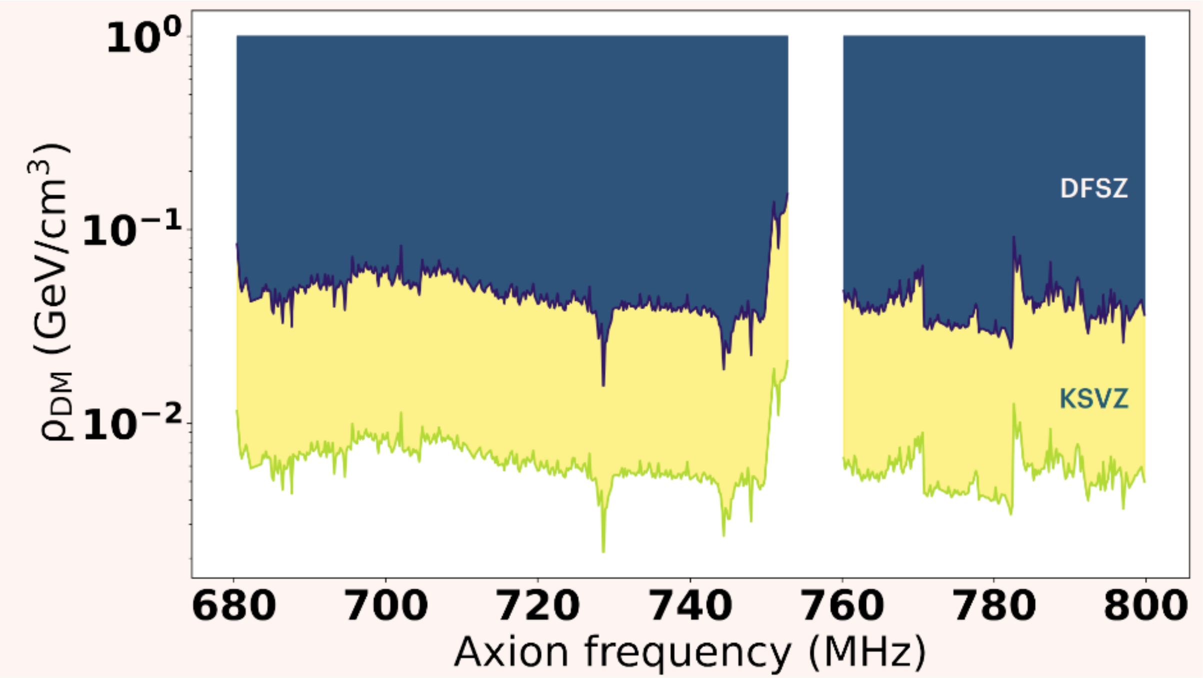
Carosi et al. PRL (2025) https://arxiv.org/abs/2504.07279

ADMX High-Resolution Results and Axion Astronomy



M. Guzzetti

Nonvirialized "extra cold" dark matter produces a narrow signal with a measurable doppler shift



M. Guzzetti, General Exam

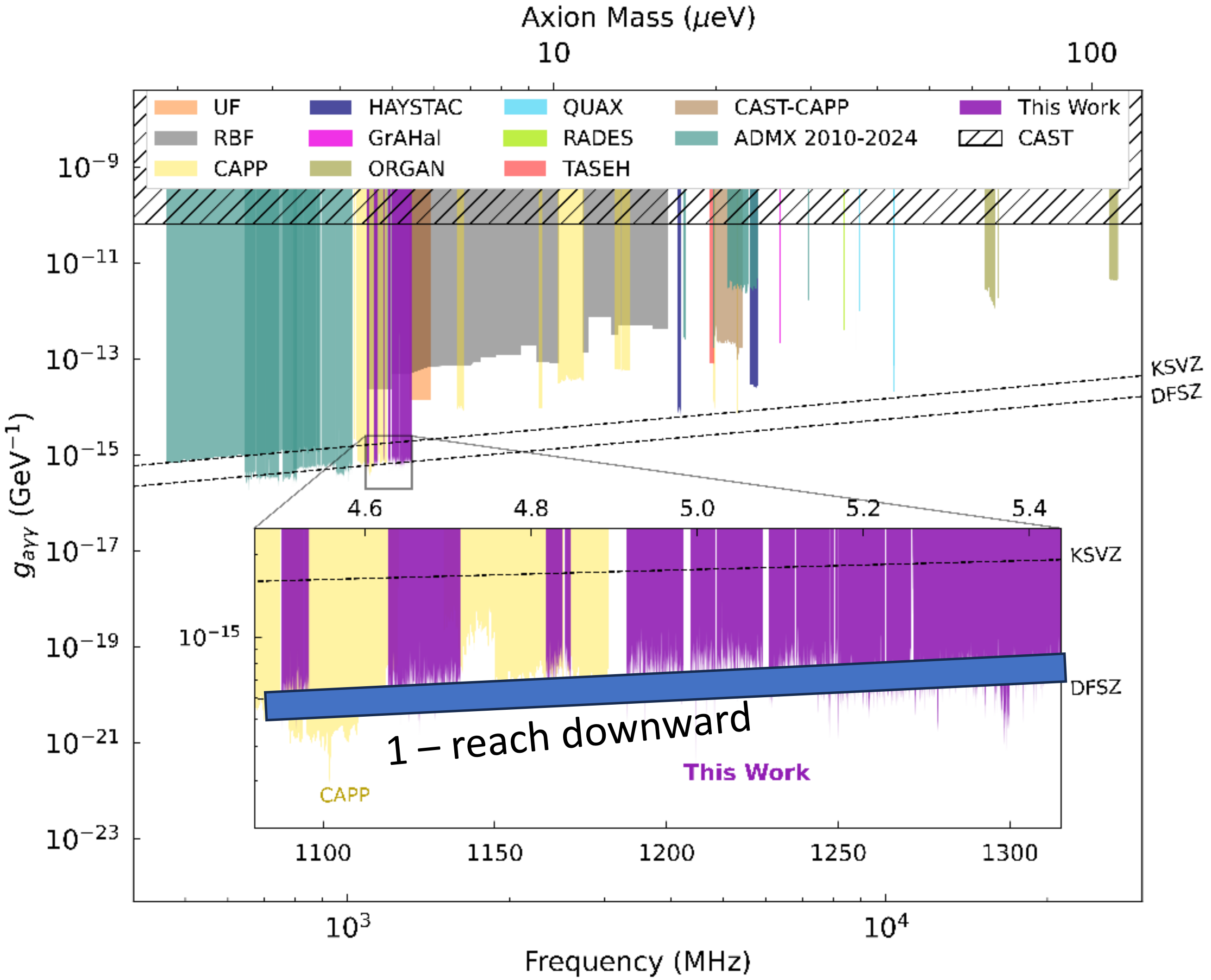
A high-resolution analysis to search for narrowband signals puts limits on dark matter axion flow densities

Bartram et al. Phys. Rev. D 109, 083014 (2024)

ADMX in the Coming Year

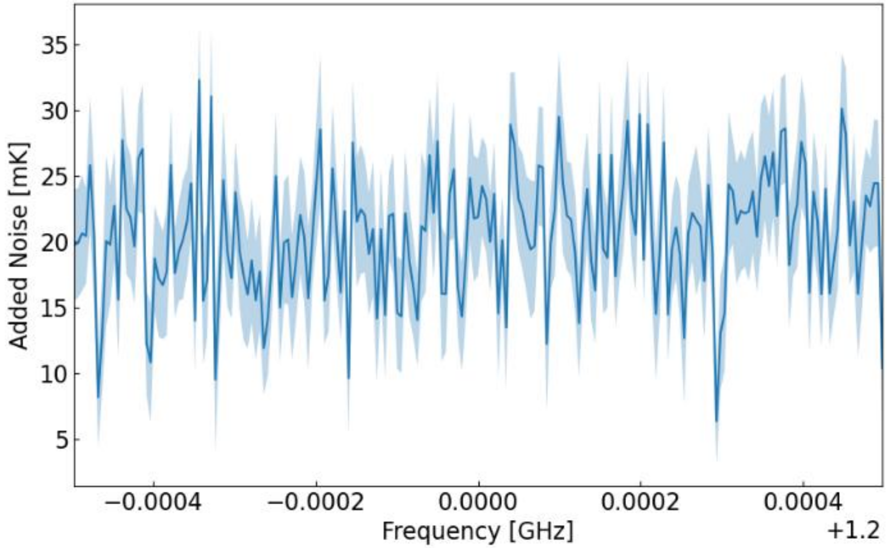
Plan: Extend reach down to DFSZ at below-nominal dark matter density

Method: Improve amplifiers to lower system noise temperature.



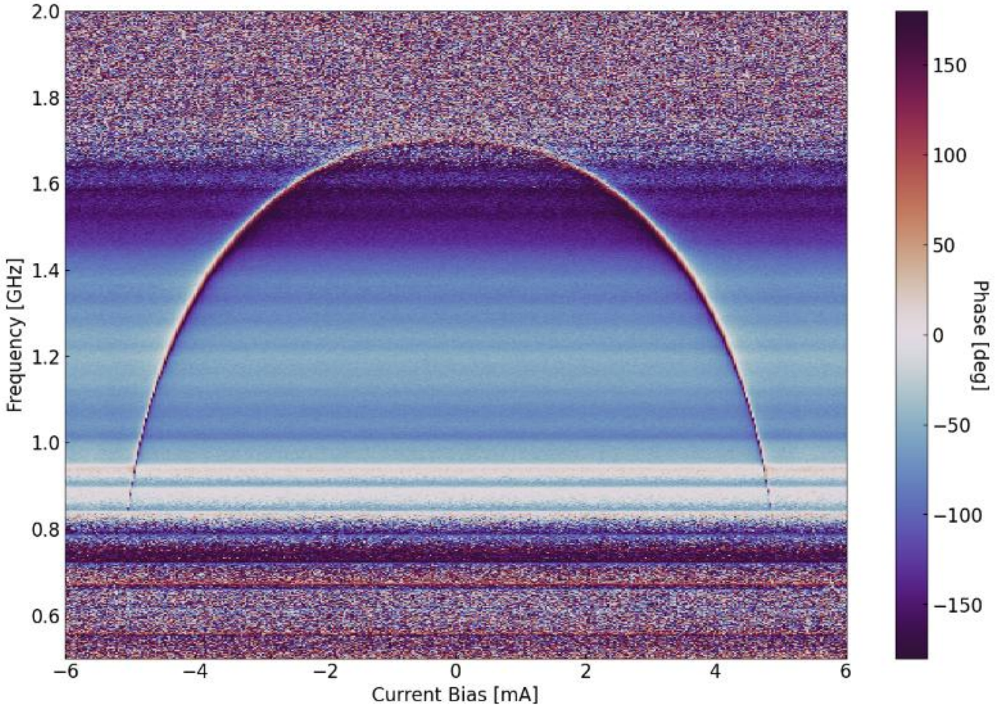
ADMX Next-Generation Amplifiers

Preliminary noise performance in ex-situ test of ADMX JPA



Noise performance 10x better than 2024 device!!

Operating Frequency vs Bias Current
Ex-situ test

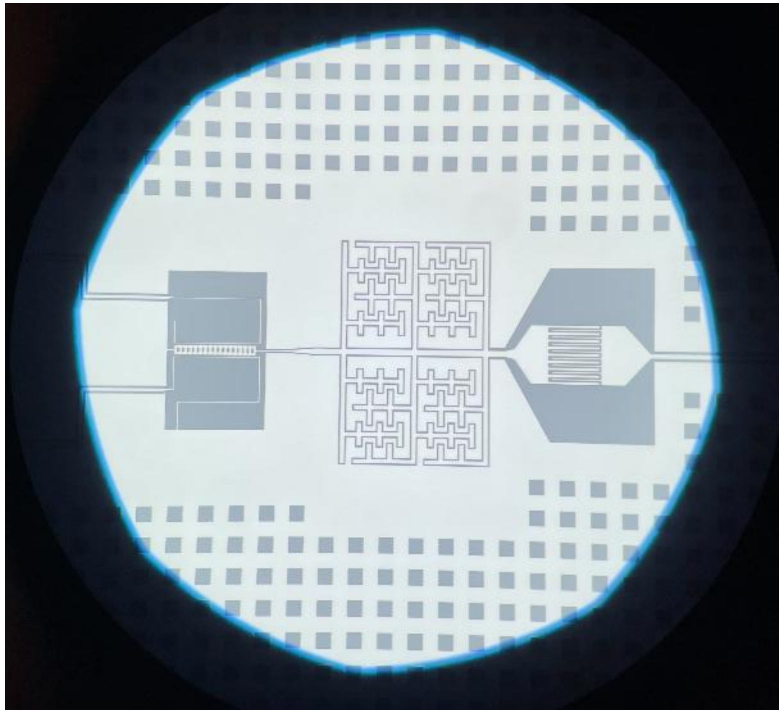


Tunable over full range

Figs. Courtesy J. Hoffman, WUSTL

ADMX Next-Generation Amplifiers

- Overall anticipated system noise improvement is decreased by a factor of x2
- This will lead to a sensitivity of √2 in axion photon coupling for a fixed dark matter density.
- Equivalently, a factor of 2 in local dark matter density for a fixed coupling

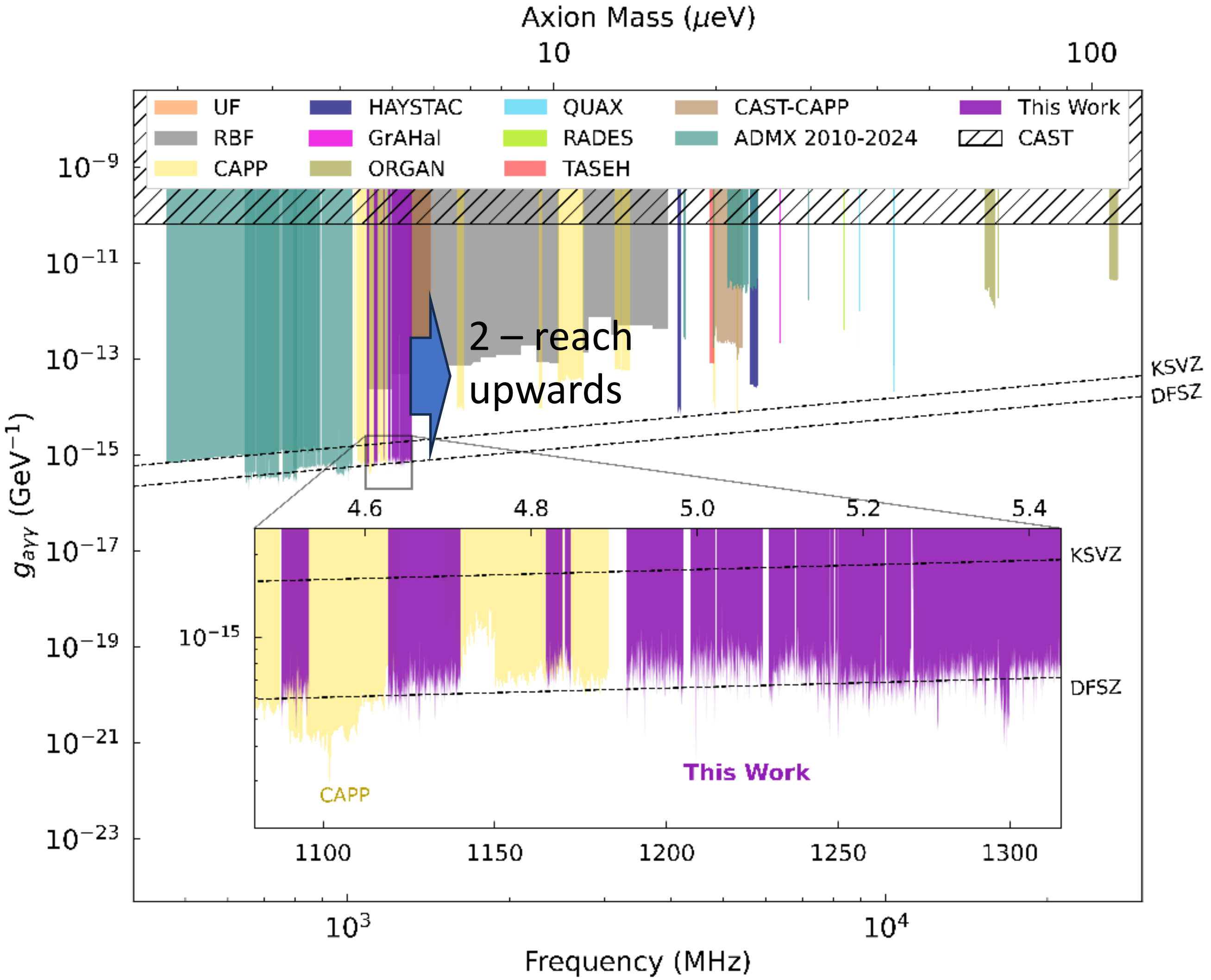


ADMX Near Future

Beyond next year:

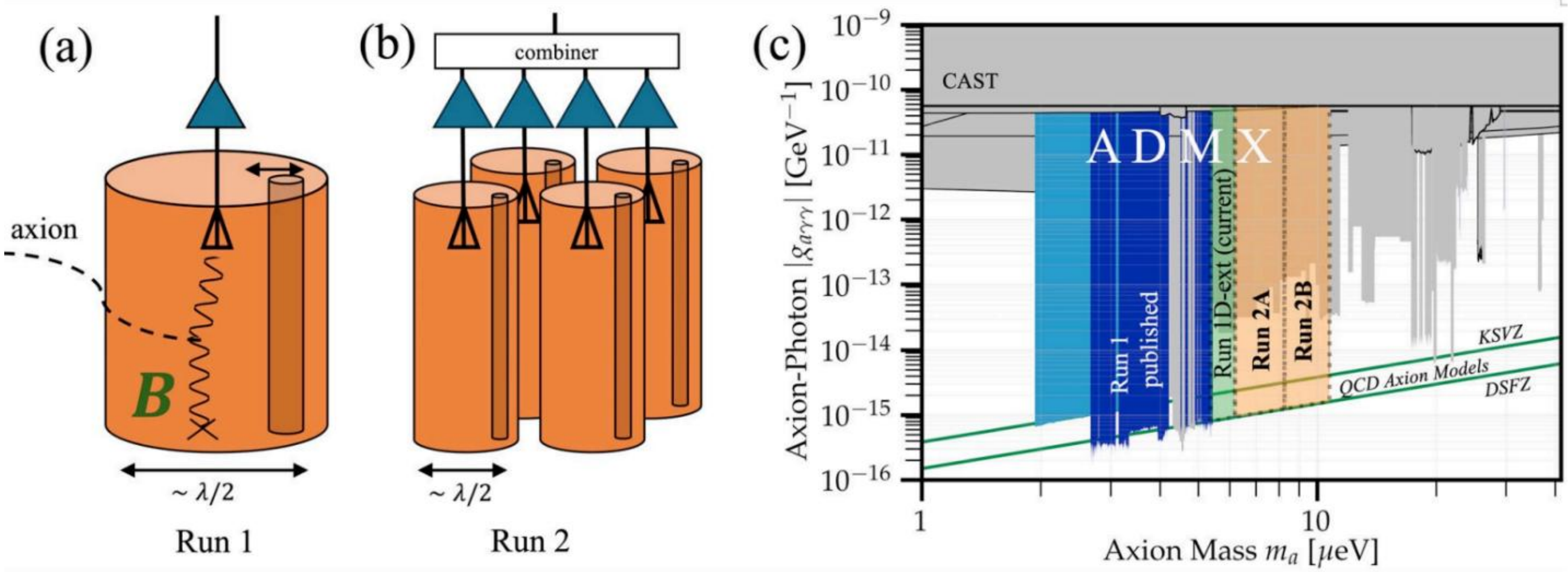
Goal: Extend sensitivity to higher masses using a multicavity system

Method: Multiple cavity system



ADMX 4-cavity system

- Reach higher frequencies with multiple resonators
- Maintain axion conversion volume with multiple cavities
- Challenge: coherent signal combining between cavities



4 cavity system - design

- 4 Cavities are independently tuned and signal is independently digitizer
- Signal combining done in same way as a multi-antenna radio telescope

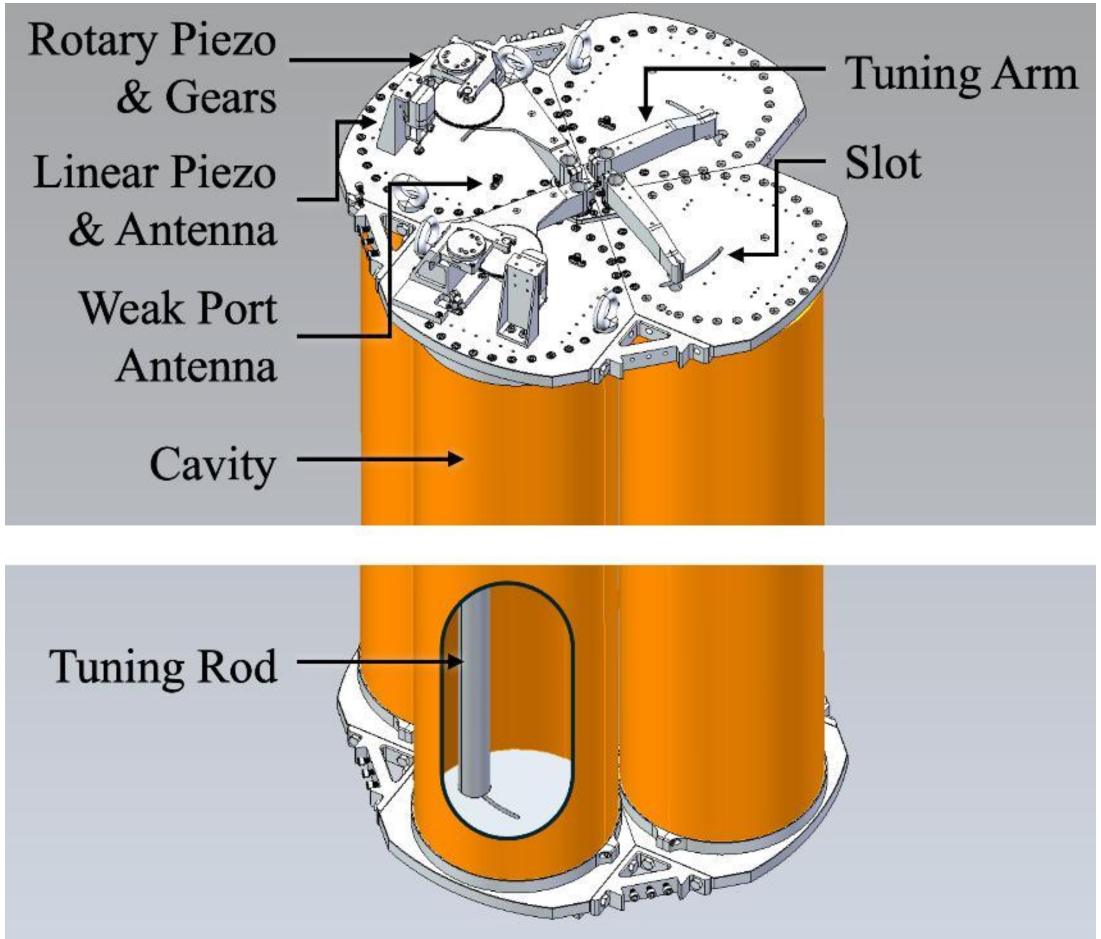


Fig. Courtesy S. Knirck, Harvard

The Future of Haloscopes

At higher frequencies, axion haloscopes suffer from unfavorable

-Volume scaling
-Resonator Q scaling
-Standard Quantum Limit noise scaling

A thorough search up to 10 GHz+ will require

- Sophisticated, high-Q Resonators
  read out by
- Sub-quantum limit detectors
  inside of
- Large, high-field magnets
  located at
- Dedicated Facilities
  operated by
- Larger Collaborations

One Possibility

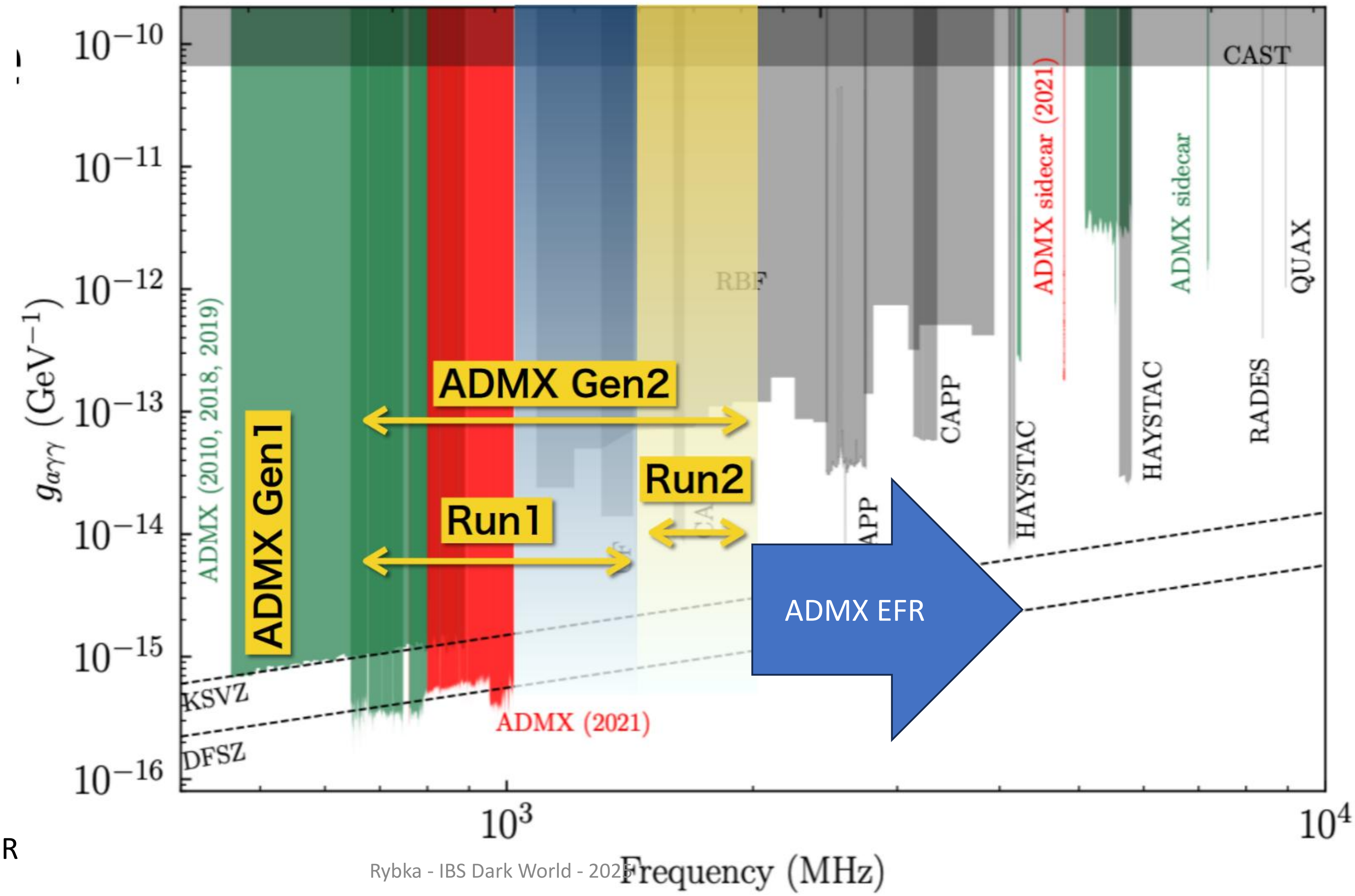
ADMX EFR

New Magnet

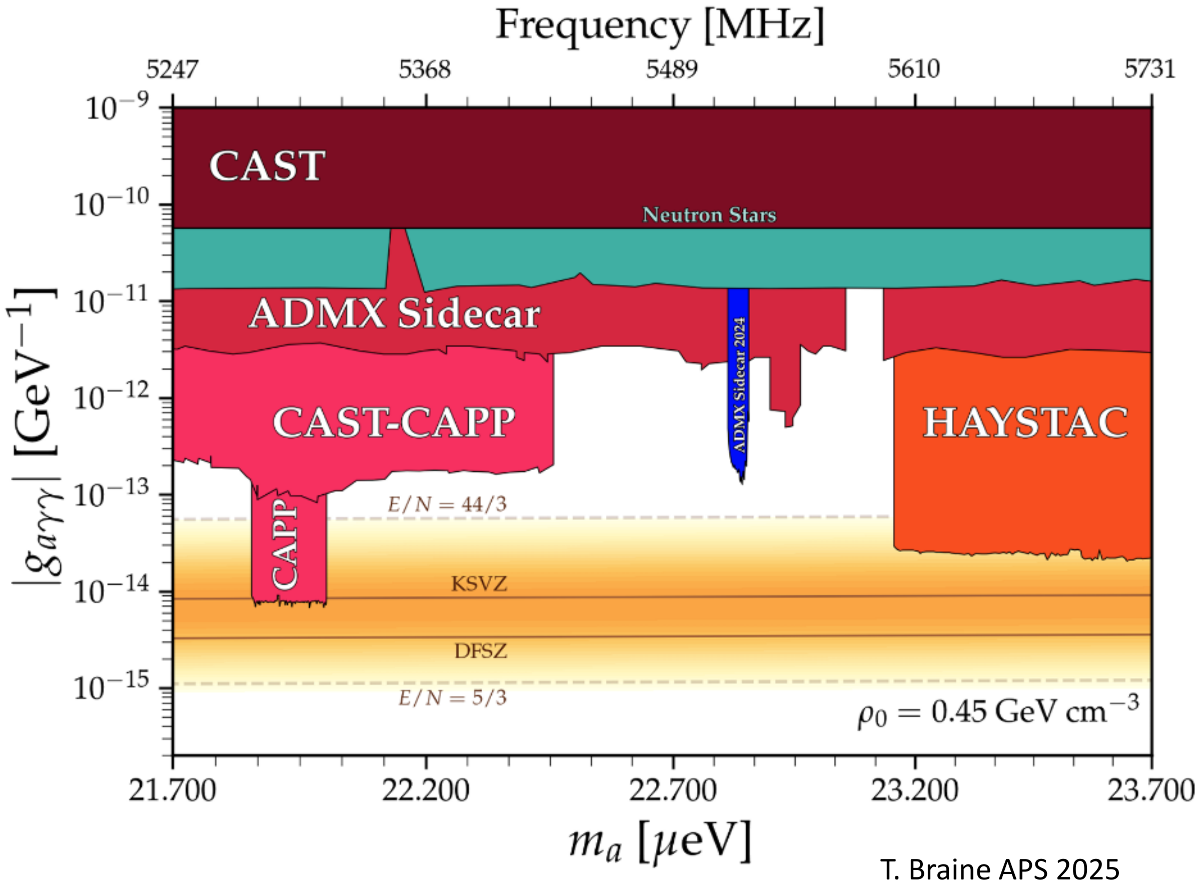
More Cavities

New Technology

New magnet at FNAL – Dark Wave Lab
Potential site of ADMX-EFR



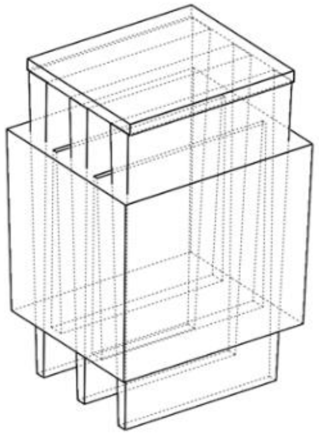
ADMX Sidecar 'hybrid-superconducting cavity'

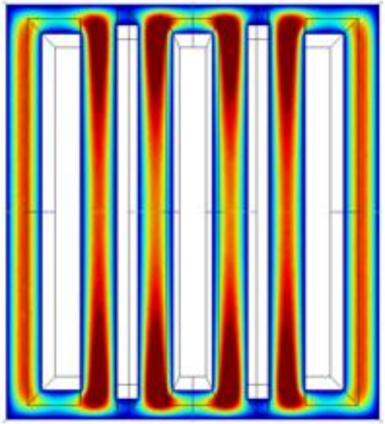


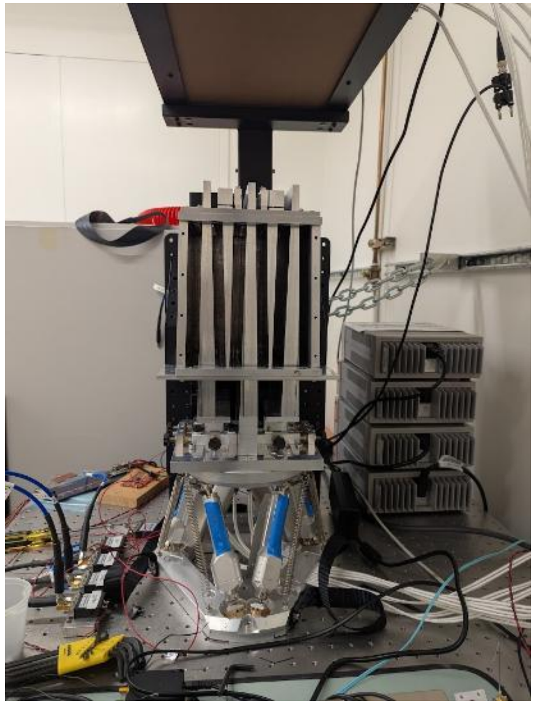
T. Braine APS 2025

- Field-tolerant superconductors allow for higher-Q cavities, increasing scan speed and sensitivity.

More advances on the way!

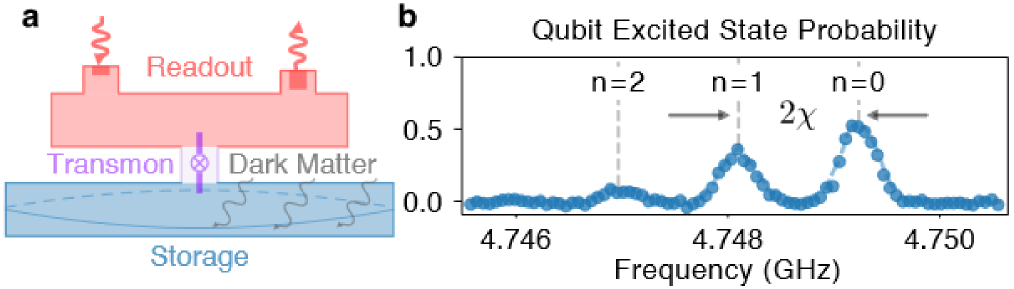






We are developing sophisticated, tunable resonators with multiwavelength volumes.

https://arxiv.org/abs/2411.13776 and 2404.06627

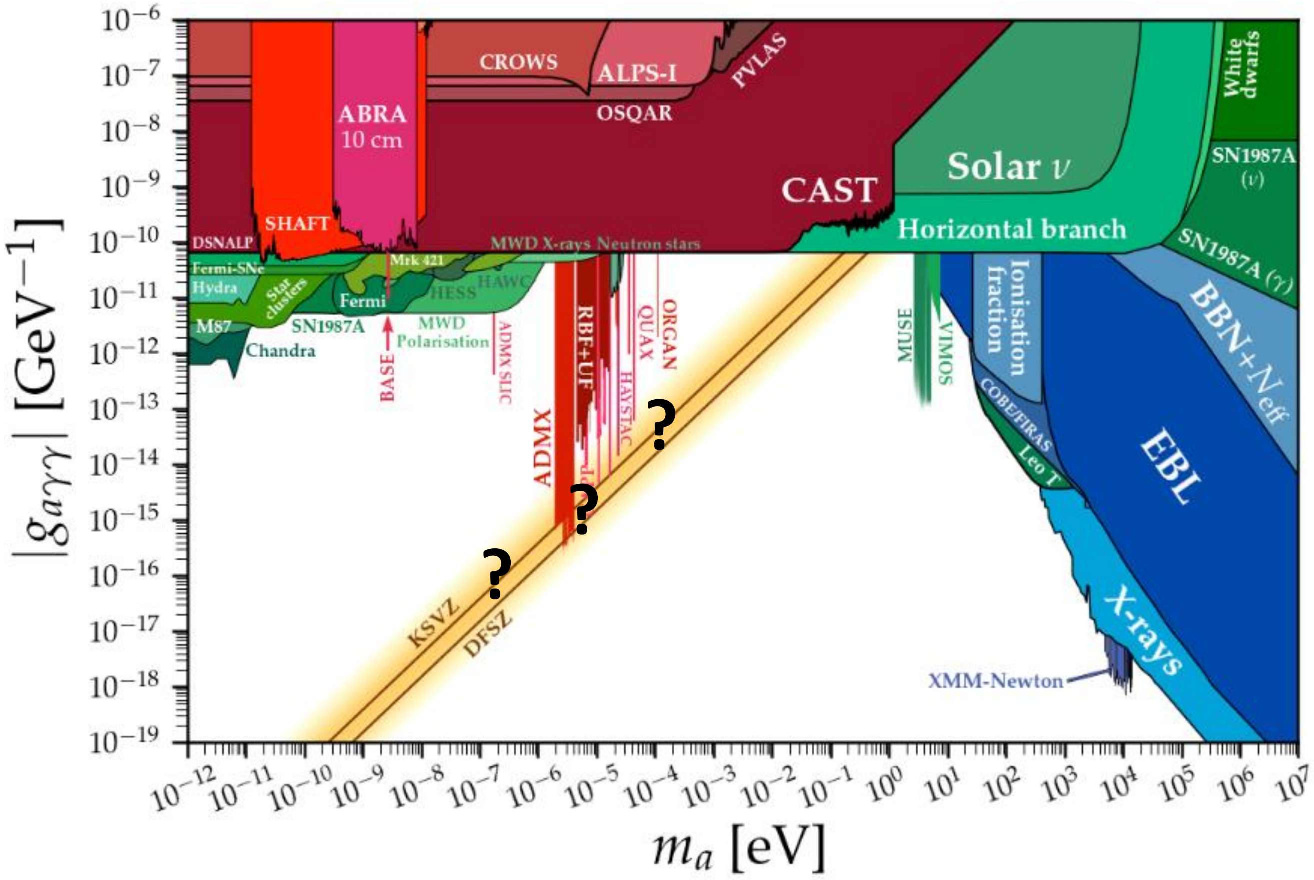


Single Photon Counting / Squeezing Becomes more important at higher Frequencies!

E.g. Qubit Based photon counting for sensitivity below the standard quantum limit (A. Dixit, PRL 126, 141302 (2021))

Consequences of Discovery

- Mass probes physics during or just after inflation
- Model predicts new Higgs sector or heavy quarks – possible accelerator signatures
- Lineshape probes local dark matter astrophysics
- Points the way to electron/nucleon coupling experiments – is it really the QCD axion?



Summary

- QCD Axion Dark Matter experiments have transitioned from an "instrument development" phase to a "discovery phase".
- ADMX is operating with the hope of a discovery over an increasingly wider frequency range, with plans to scale larger.
- Emerging technologies have great potential to improve axion haloscopes
- We are scaling up axion experiments to make the discovery a reality. Global cooperative efforts are improving things!