

Axion Dark Matter Searches

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UGRP, Institute of Science Tokyo Sept 28, 2026



Wave-like Dark Matter Candidates

Wave-like Definition: Mass < 1 eV

Broad Candidate Categories:

- Pseudo-scalar*
- Scalar
- Vector

Production: Athermal production (misalignment).

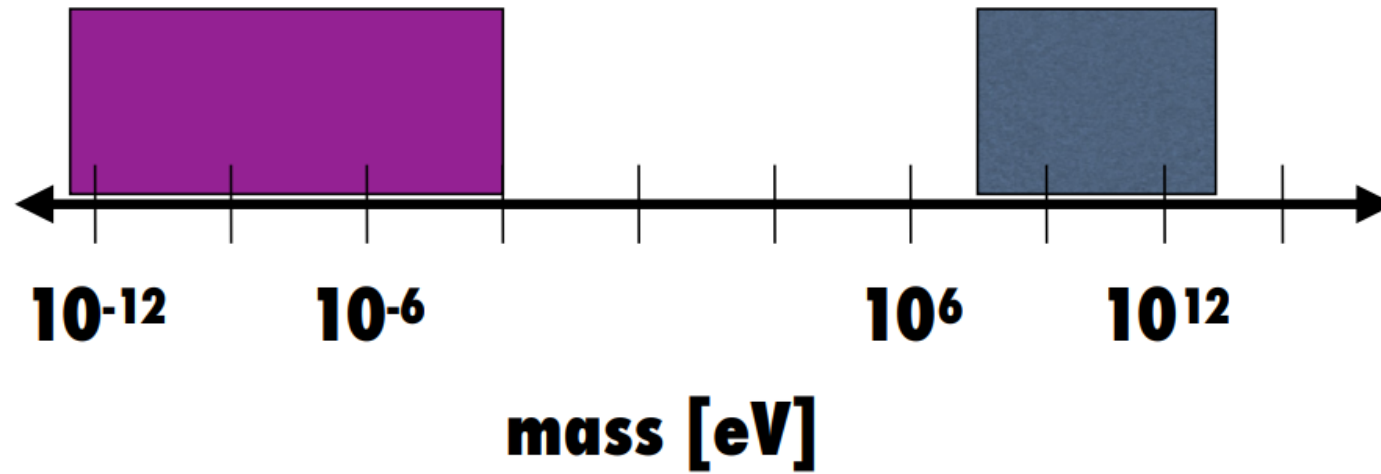
Detection: Coherent interaction of the wave with the detector. Resonant amplification often key.



**The most famous candidate in this group is the QCD axion.*

Wavelike Dark Matter

WIMP Dark Matter



de Broglie Wavelength - $\lambda_{dB} \approx \frac{2\pi}{mv}$

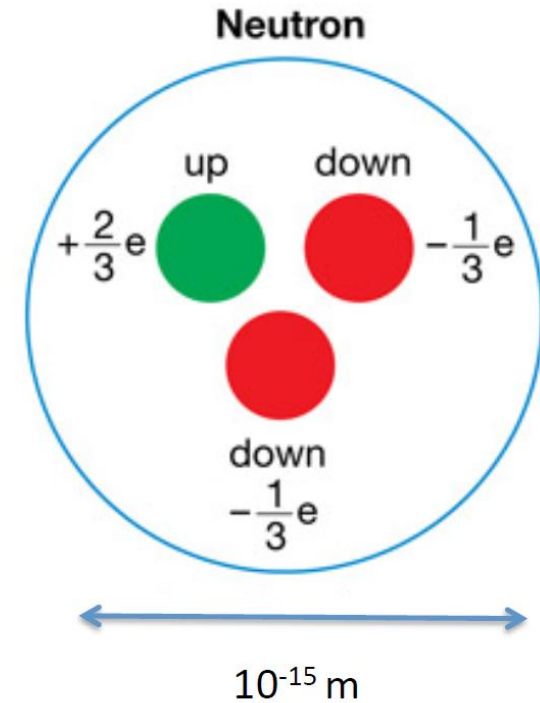
Occupancy Number - $N \approx \frac{\rho_{DM}}{m} \lambda_{dB}^3$

- Axion ($m \sim 10^{-9}$ eV): $\lambda_{dB} \sim 10^4$ km with $N \sim 10^{44}$
- WIMP ($m \sim 100$ GeV): $\lambda_{dB} \sim 10^{-16}$ km with $N \sim 10^{-36}$

where $\rho_{DM} = 0.4 \text{ GeV/cm}^3$.. . Adapted from B. Safdi

The QCD Axion: Motivation

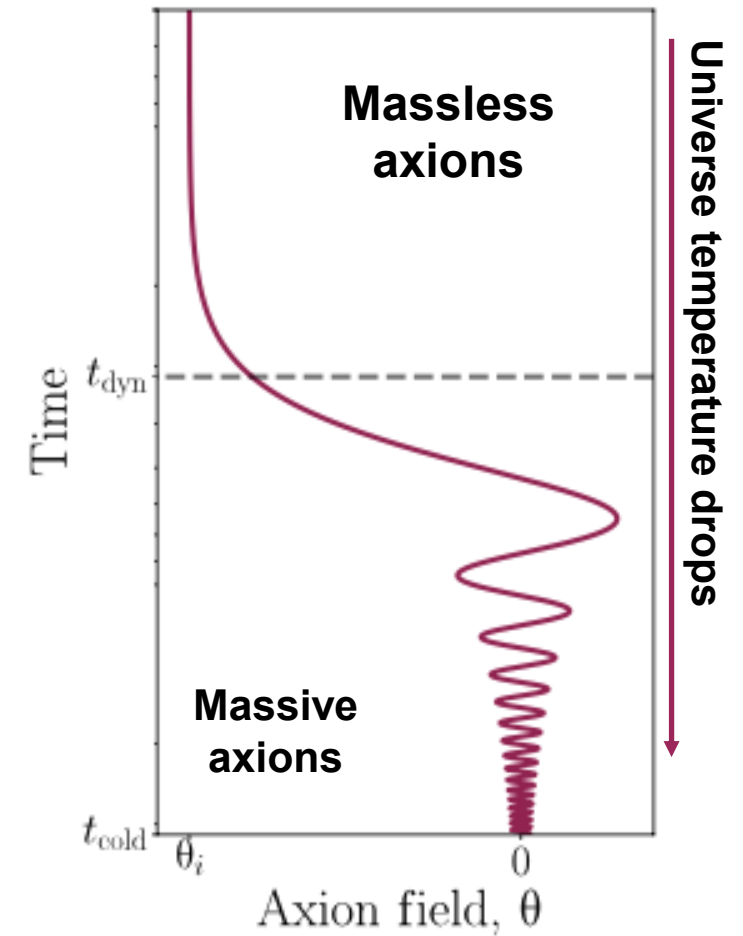
- QCD is naturally CP violating from phenomena like QCD-instantons
- One naively expects a neutron electric dipole moment of 10^{-16} e cm
- But nEDM is measured to be below 1.3×10^{-26} e cm (*Abel, 2020*)
- The best explanation? New U(1) axial symmetry, that when broken, cancels CP violation in the strong sector (*Peccei, Quinn, 1977*)
- Consequence: New particle, called the axion (*Weinberg, Wilczek, 1978*)



$$d = 10^{-16} \text{ e cm} \\ < 3 \times 10^{-26} \text{ e cm}$$

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](https://arxiv.org/abs/1803.08127)

Detecting Axions

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

Coupling to Photons

Coupling to Nucleon EDM

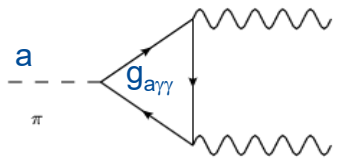
Coupling to Axial Nuclear Moment

Coupling to Axial Electron Moment

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

Detecting Axions

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



Coupling to Photons

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

Coupling to Nucleon EDM

Coupling to Axial Nuclear Moment

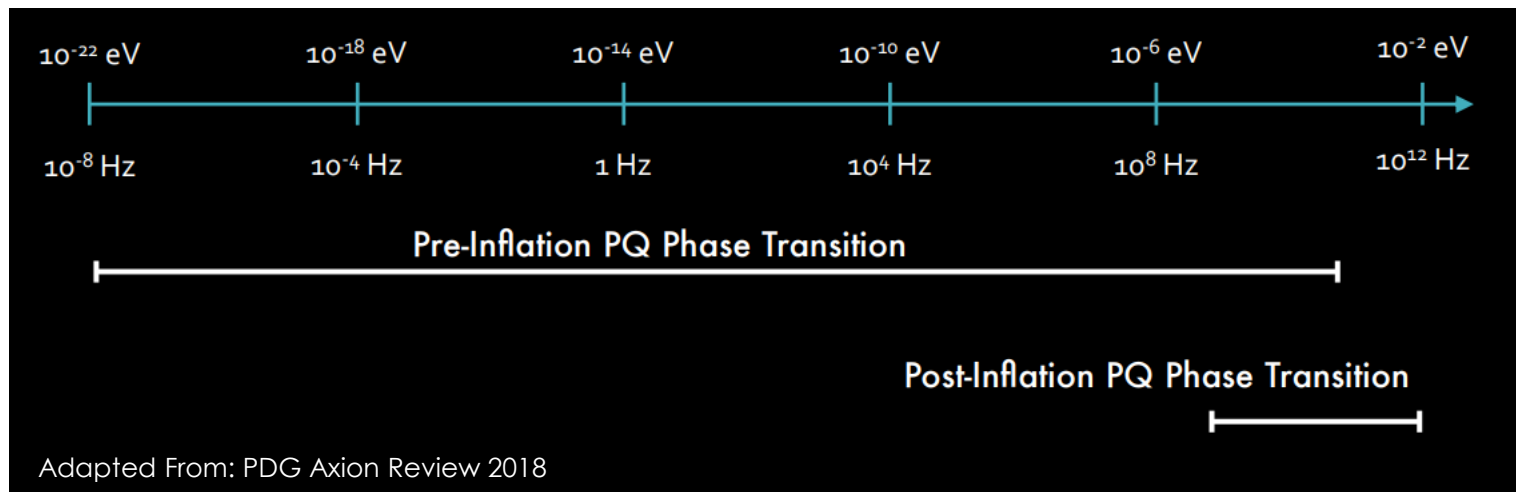
Promising experimental techniques under development

Coupling to Axial Electron Moment

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

Theoretical Preferences on Scale from Dark Matter

- 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

Limitations of this talk

- I will focus on techniques specifically for axion dark matter, with only a small number of axion-like-particle or non-dark-matter axion searches.
- I will favor talking about terrestrial experiments over astrophysical inferences.
- I will specialize on the most active technique, the axion haloscope, with ADMX as the prime example.
- Apologies if I omit your favorite axion experiment. Please bring it up in the questions!

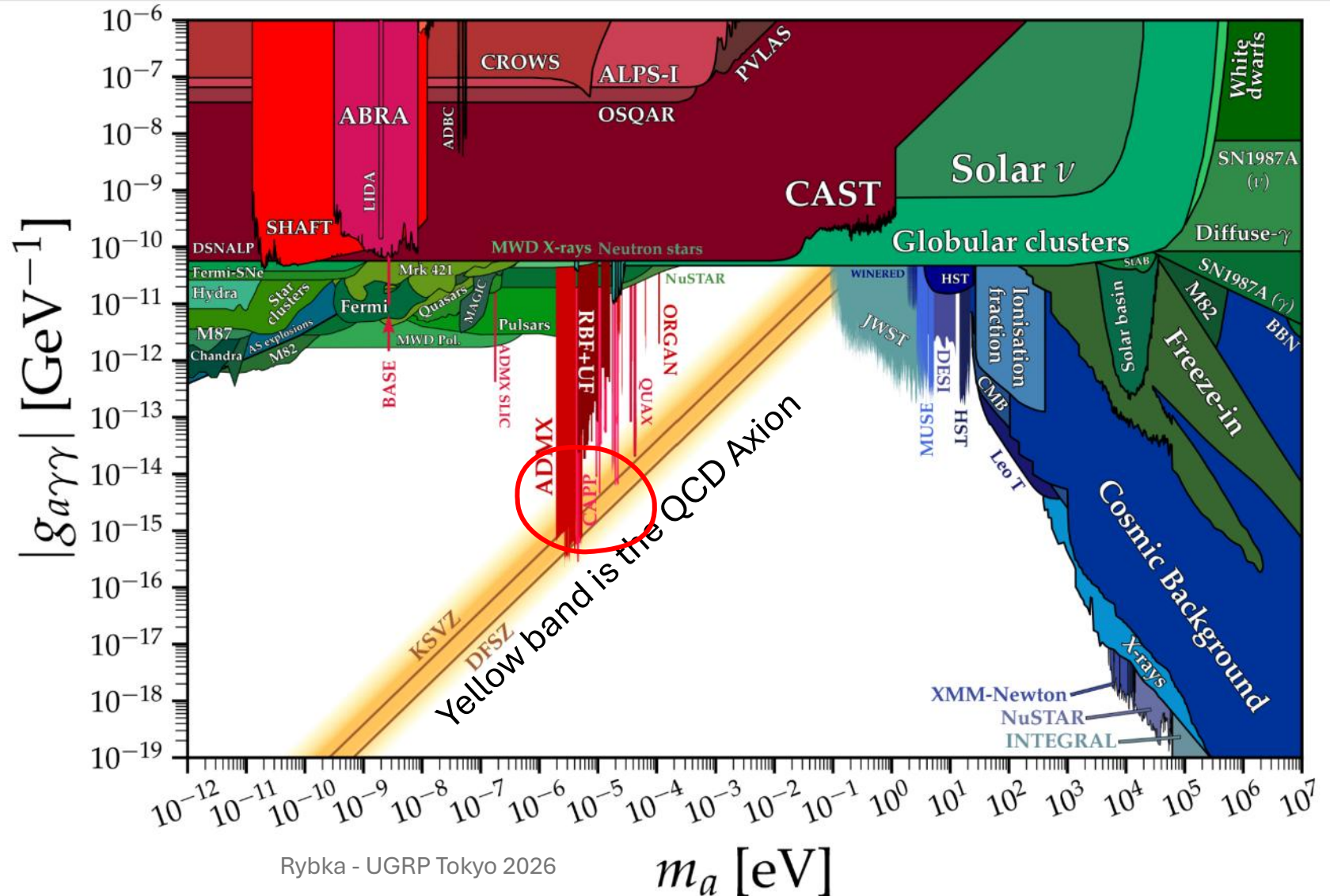
Axion Target Region

[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

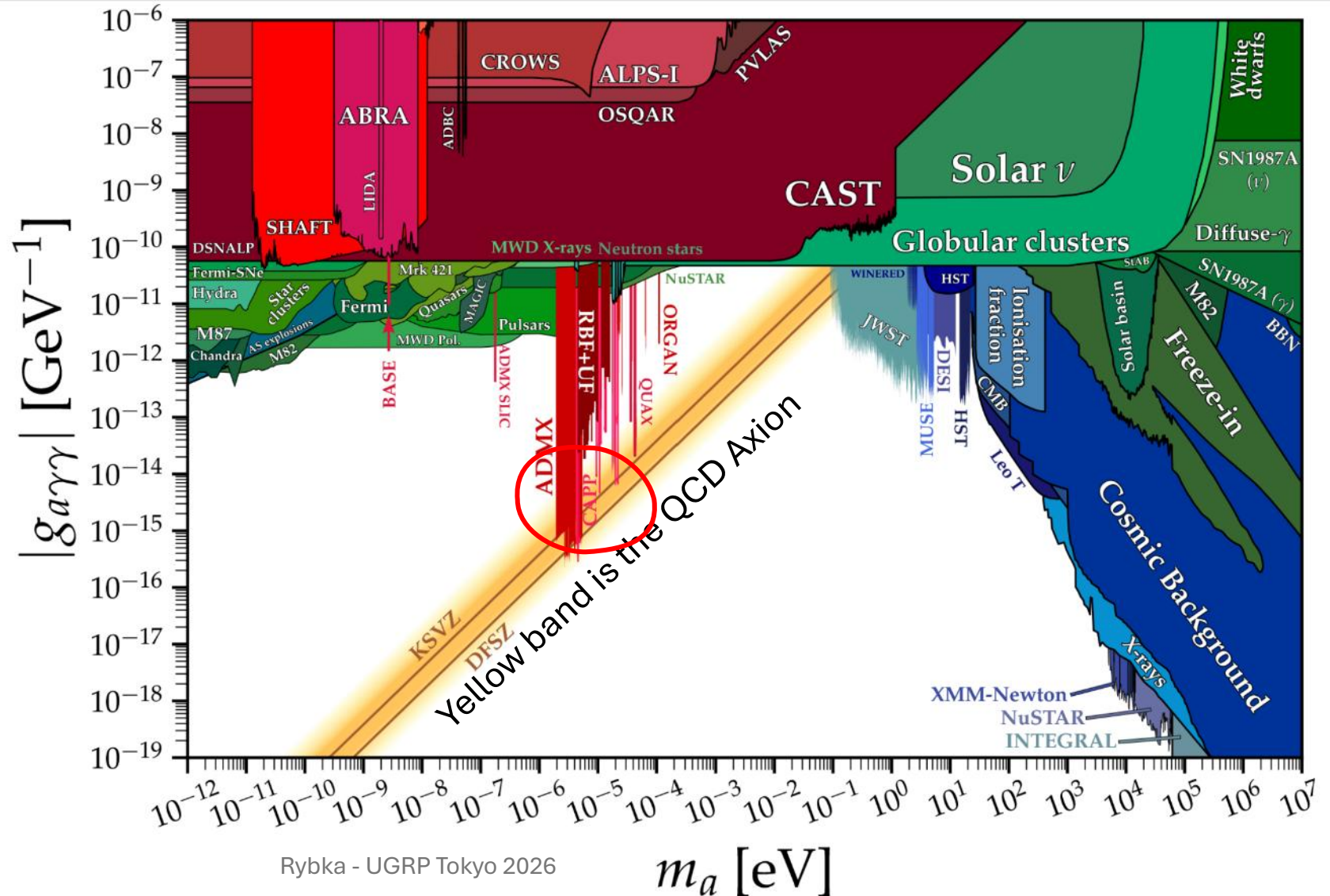


Highlighted Non-DM Experiments

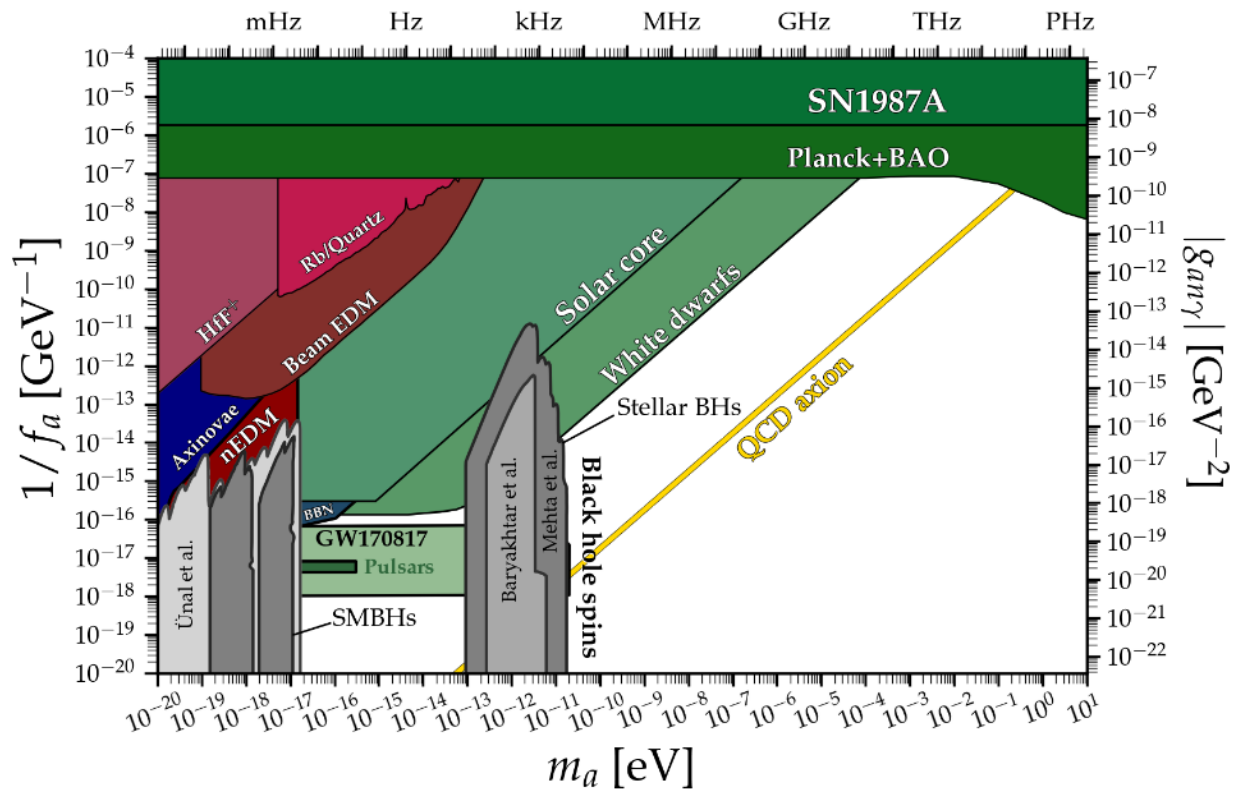
[GitHub - cajohare/AxionLimits: Data, plots and code for constraints on axions, axion-like particles, and dark photons](#) - includes zoom-in later on, updated Oct 2025

Axion Helioscopes: CAST (and SUMICO) Axions are produced in the sun and converted to keV gamma rays in a magnet on earth for detection. IAXO is under preparation targeting the QCD region at eV scales. (arXiv: 2504.00079)

Light-Shining-Through-Walls: ALPS (and many others) Laser photons are converted into axions in a magnet field and back. ALPS-II aims for a sensitivity competitive to Helioscopes. (arXiv: 2512.14110)

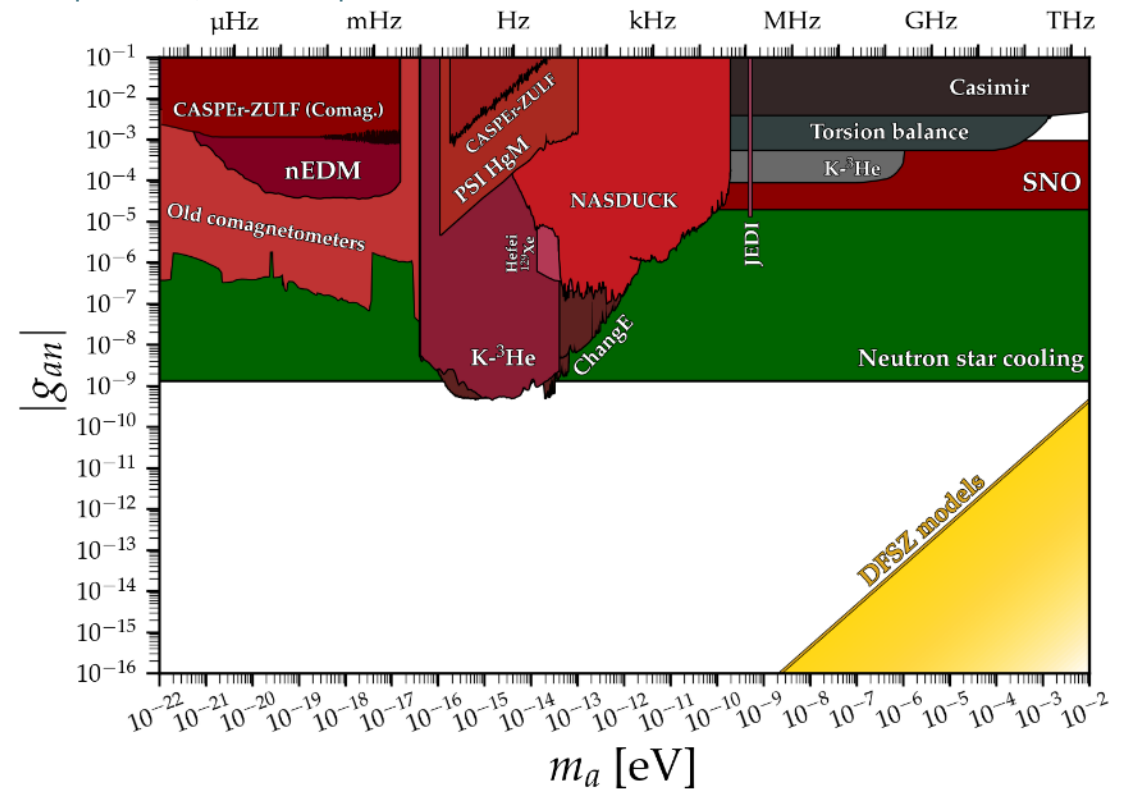


Some Non-E&M Axion Bounds



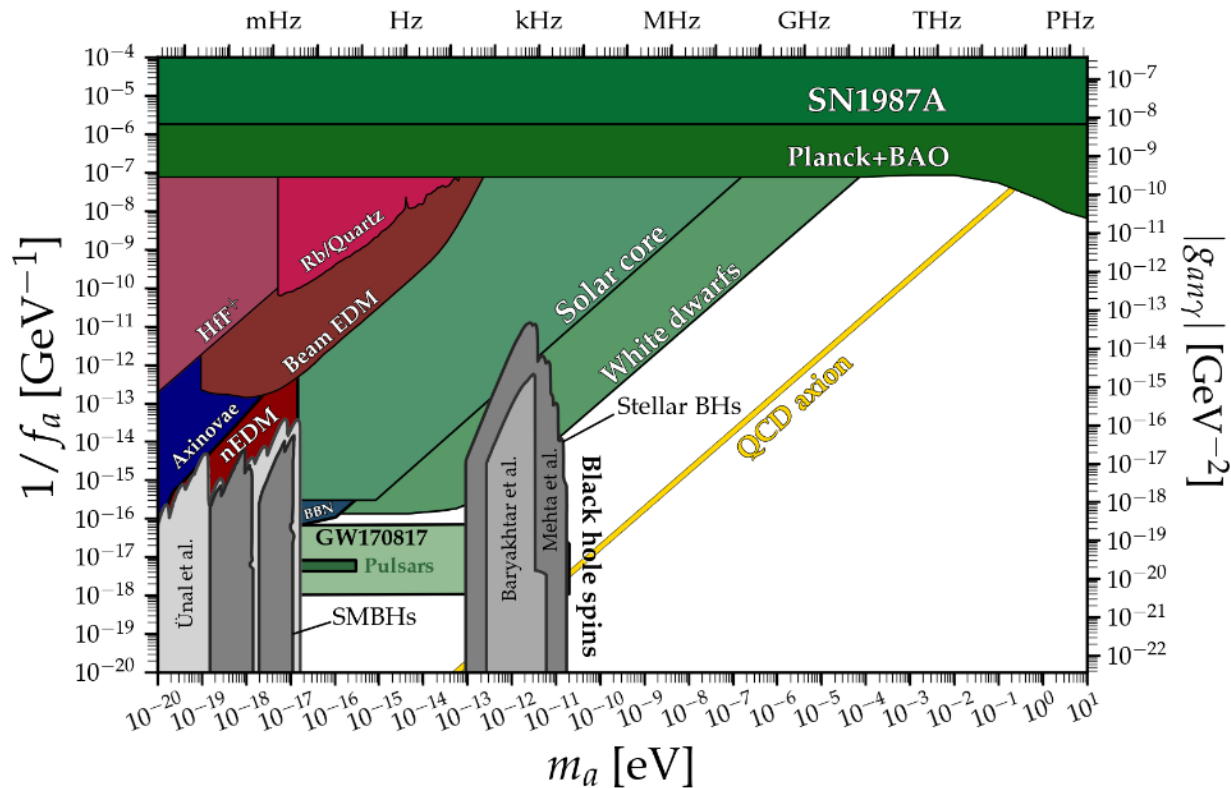
Less coupling dependent bounds

[GitHub - cajohare/AxionLimits: Data, plots and code for constraints on axions, axion-like particles, and dark photons](https://github.com/cajohare/AxionLimits)



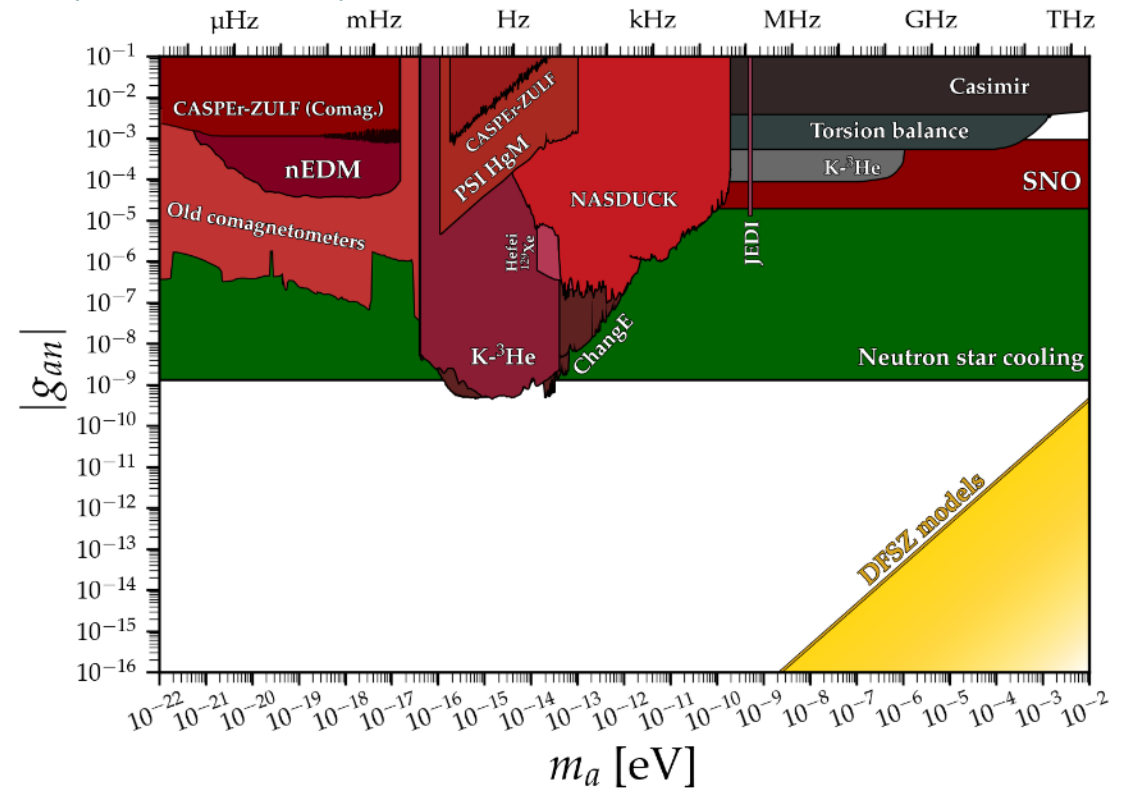
Axion-neutron bounds

Highlighted non-E&M experiments



Black holes can lose spin to axion clouds via superradiance.

[GitHub - cajohare/AxionLimits: Data, plots and code for constraints on axions, axion-like particles, and dark photons](https://github.com/cajohare/AxionLimits)



Axion dark matter coupling to nucleons causes nuclear spins to precess in a magnetic field (CASPER and others)

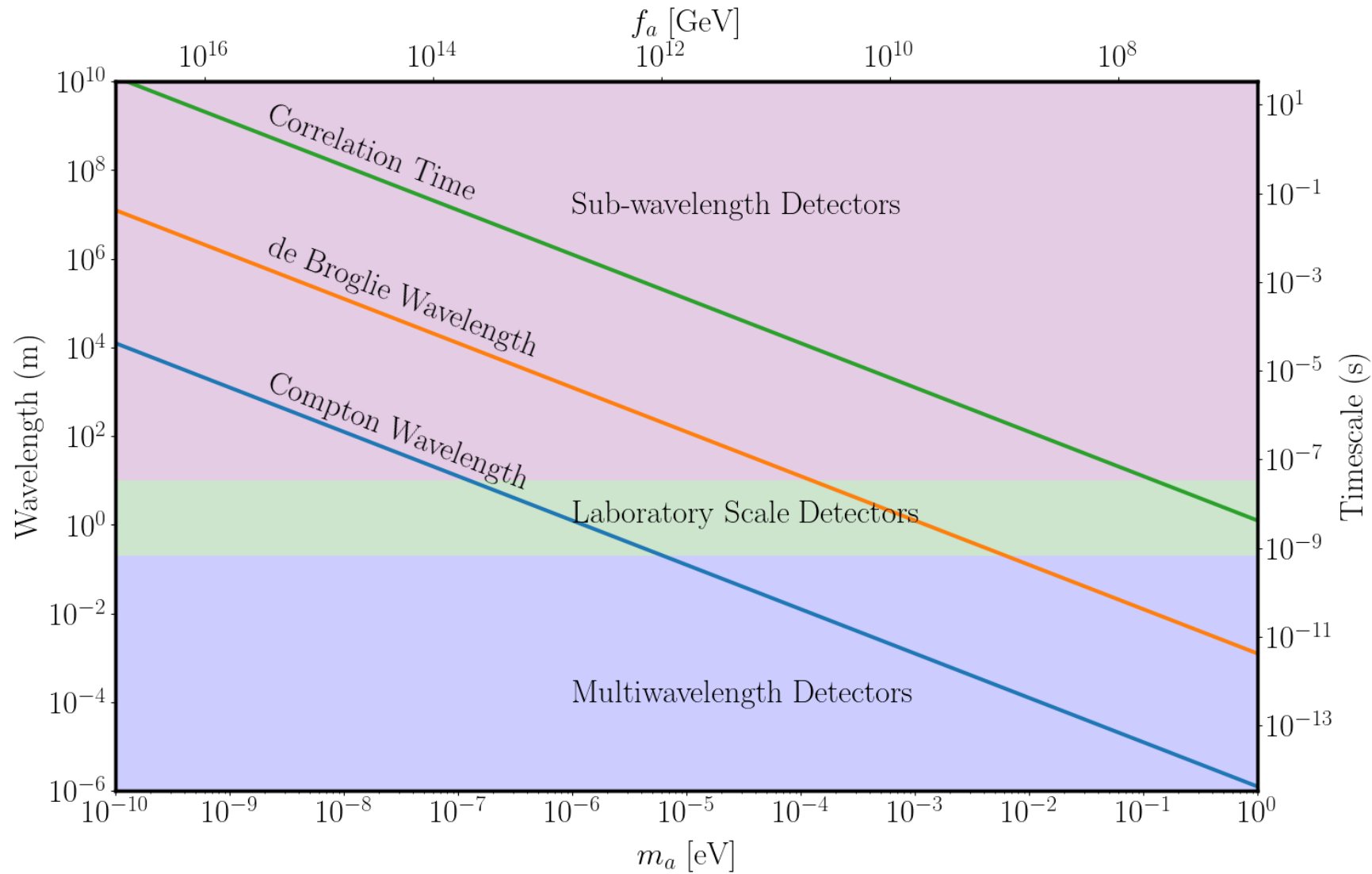
Maxwell's Equations with an Axion Field

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

$$\begin{aligned}\nabla \cdot E &= \rho - g_{a\gamma\gamma} B \cdot \nabla a \\ \nabla \times E &= -\frac{\partial B}{\partial t} \\ \nabla \times B &= \frac{\partial E}{\partial t} + J - g_{a\gamma\gamma} (E \times \nabla a - B \frac{\partial a}{\partial t}) \\ \nabla \cdot B &= 0\end{aligned}$$

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

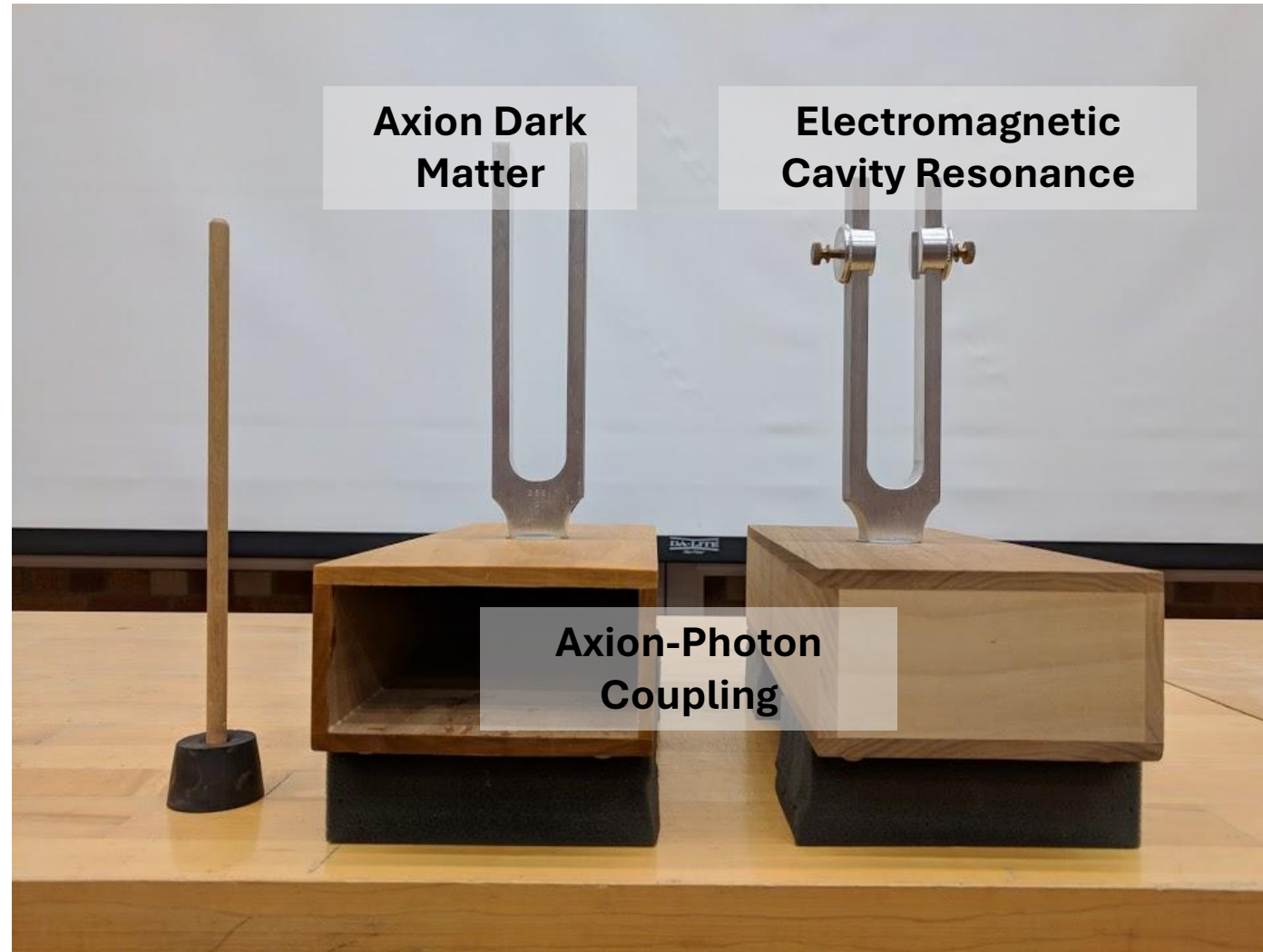
Axion Detector Length and Time Scales



Axion Haloscope for my Intro Physics Class

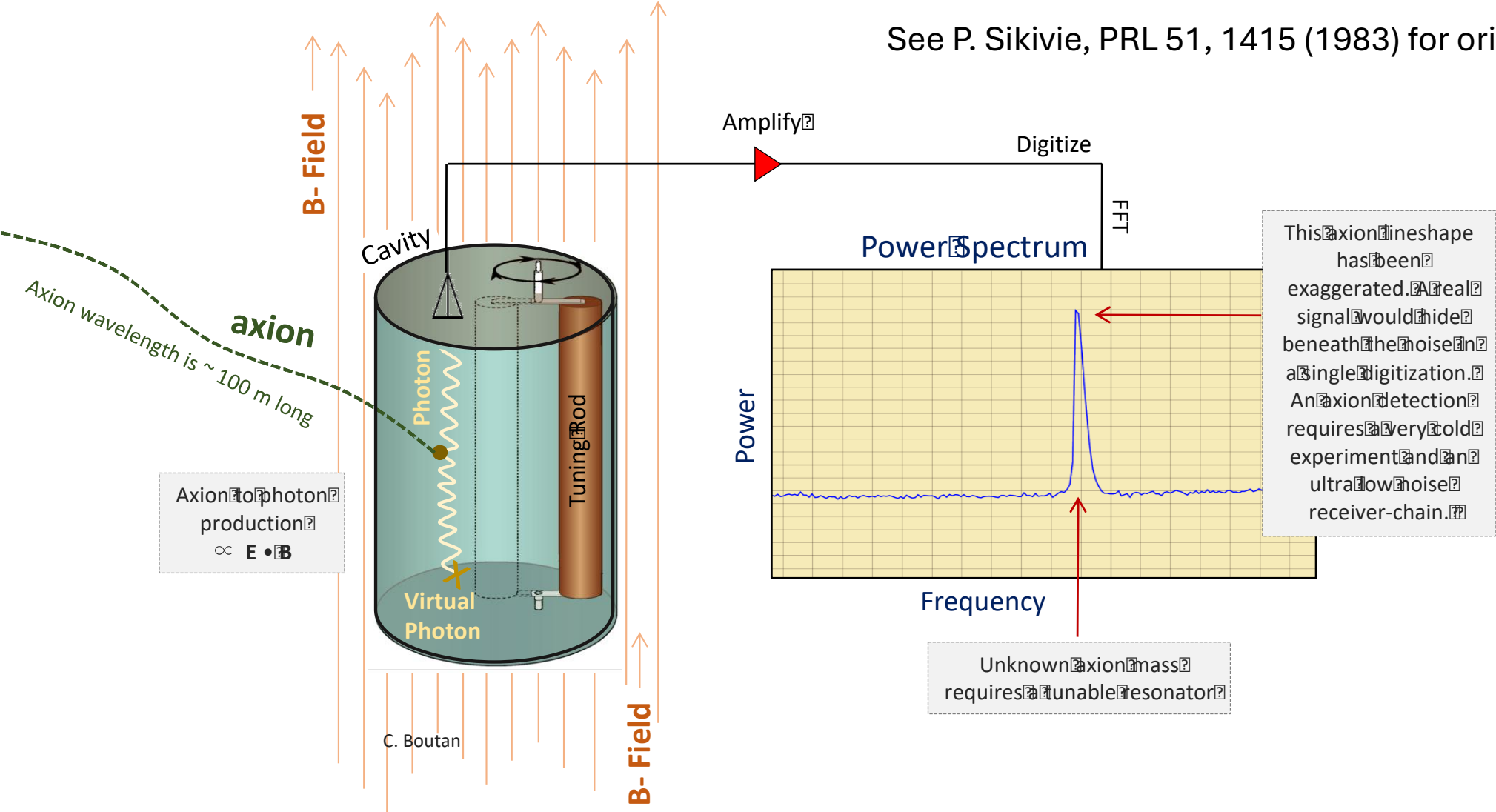


Axion Haloscope for my Intro Physics Class

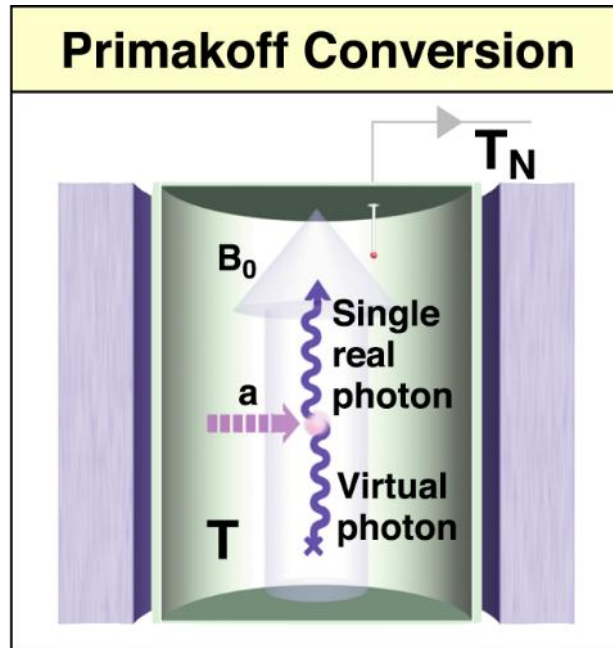


Principle of the Sikivie Axion Haloscope

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.

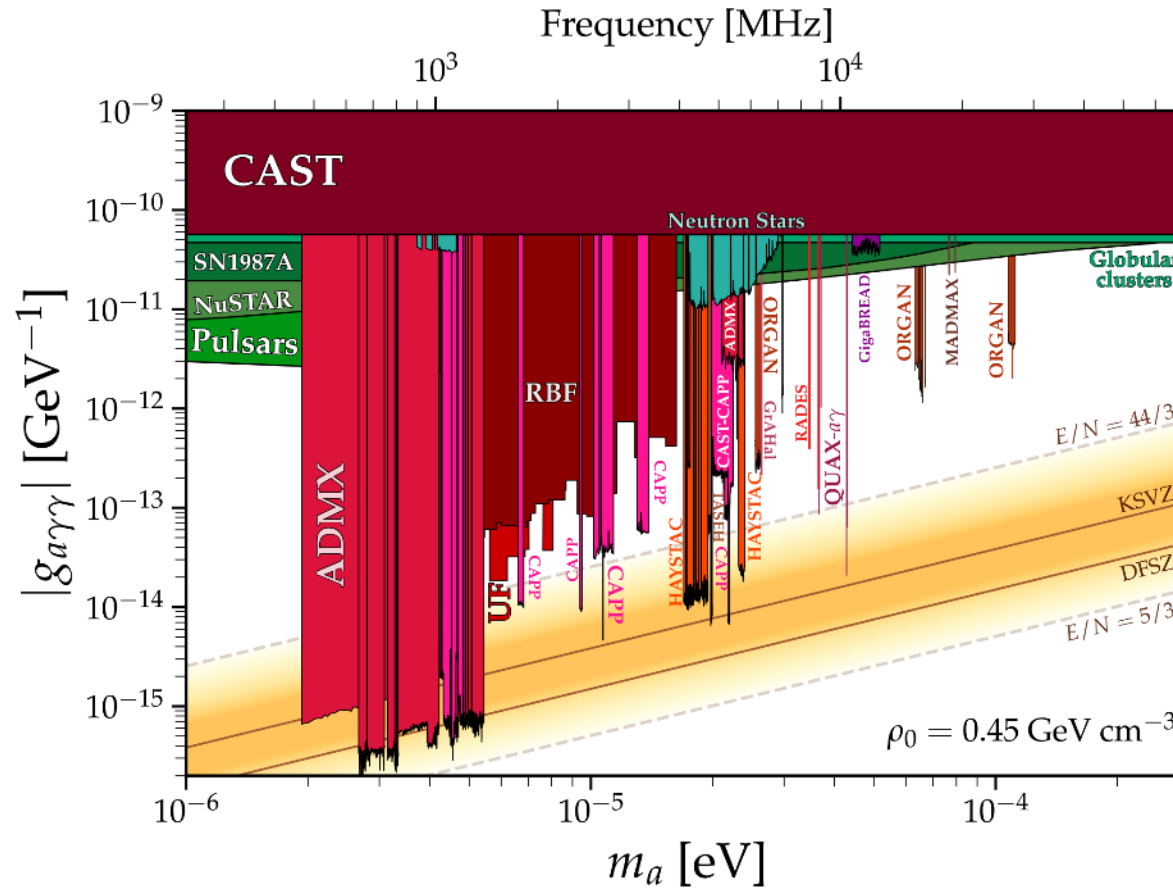
The conversion rate is enhanced if the photon's frequency corresponds to a cavity's resonant frequency.

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. I will highlight ADMX as an example.

ADMX Collaboration



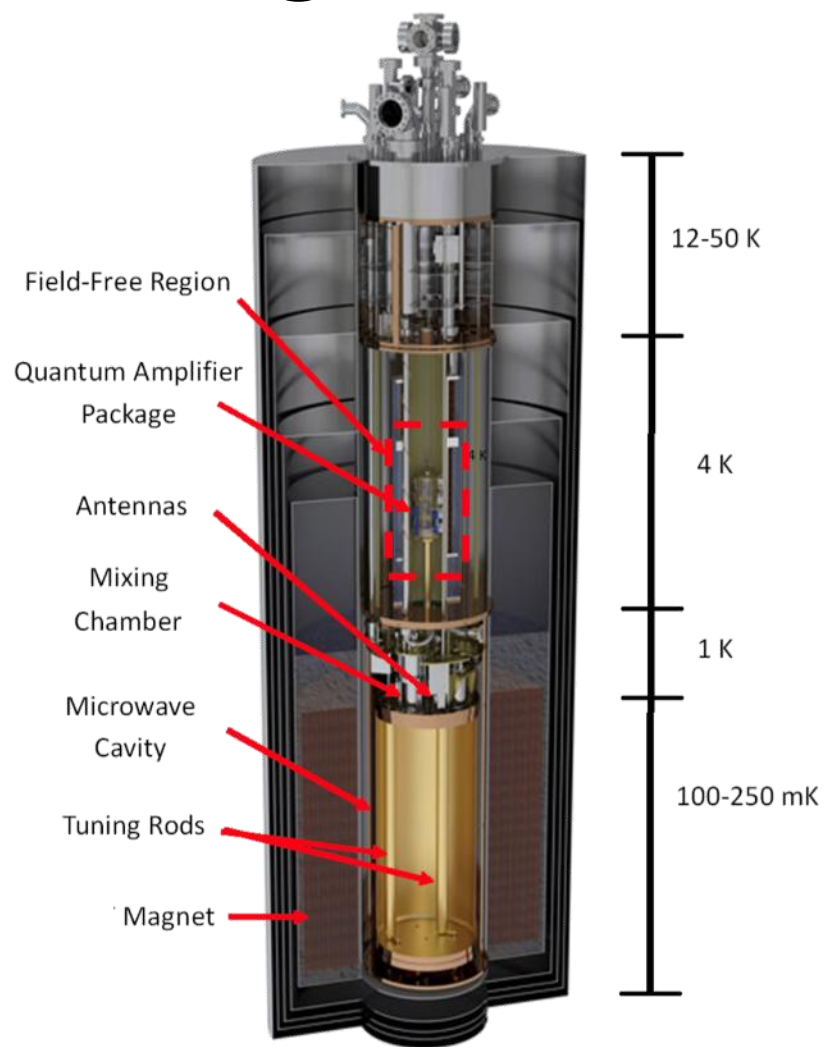
ADMX Collaboration meeting – UW - Jan 2023

Collaborating Institutions:

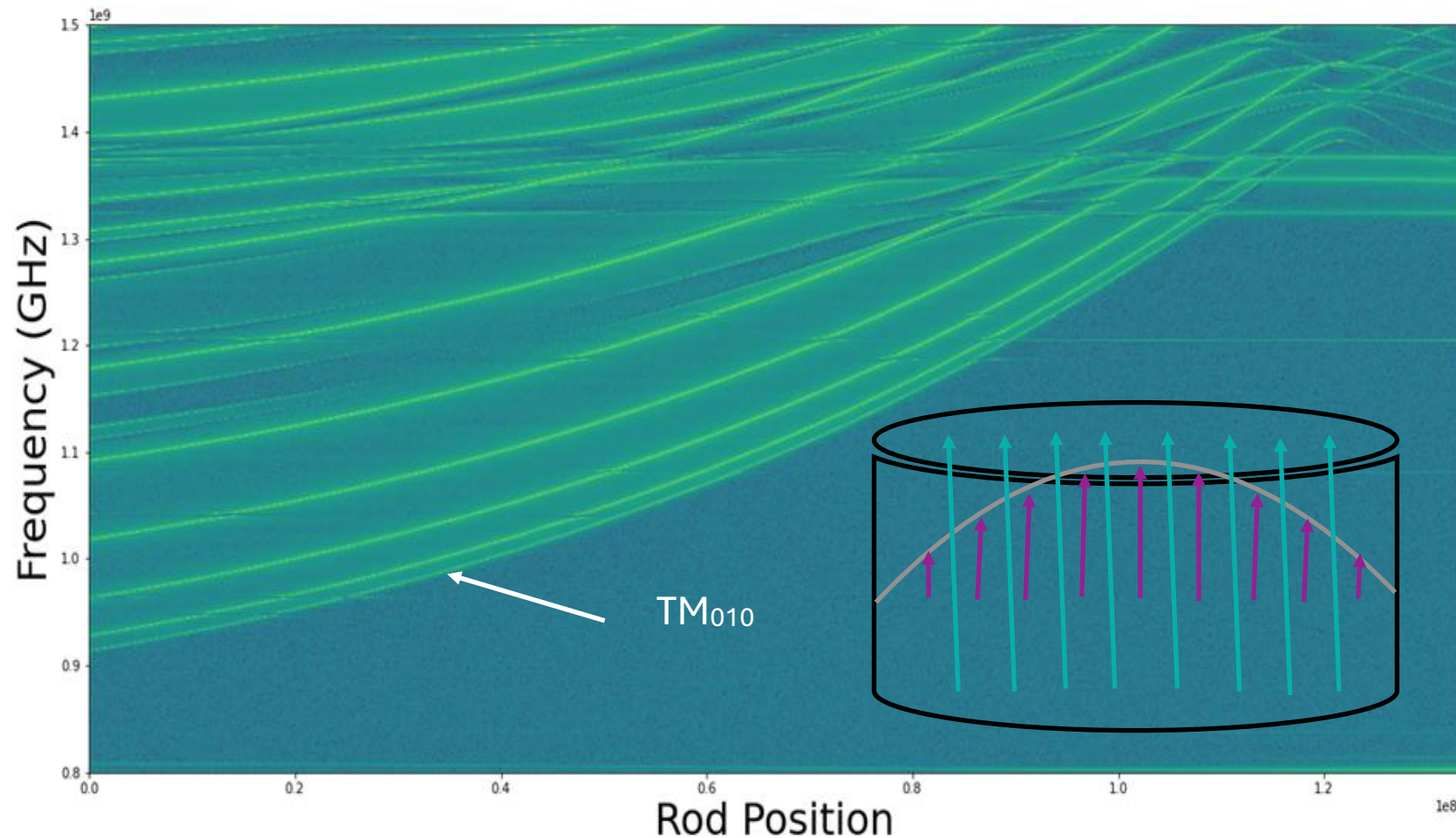
University of Washington
Washington University St. Louis
University of Western Australia
University of Florida
University of Sheffield
University of Western Australia
Stanford University / SLAC
UC Berkeley
Fermilab
Pacific Northwest National Laboratory
Lawrence Livermore National
Laboratory
Los Alamos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

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ADMX Design



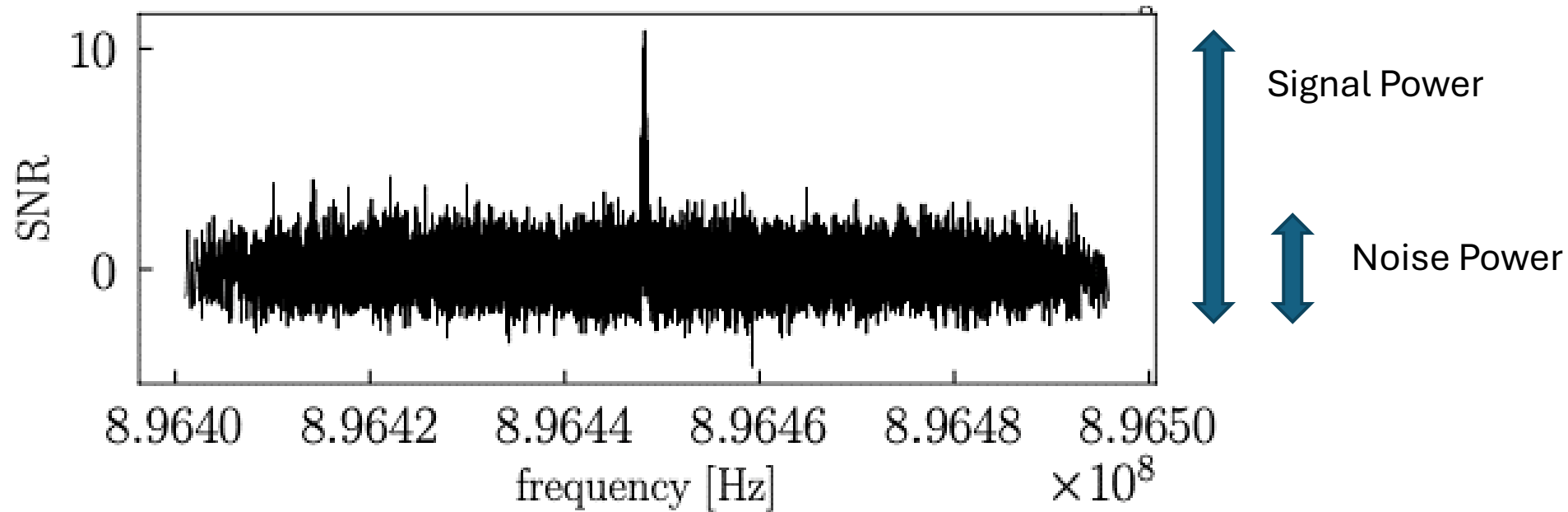
Tuning the Cavity Resonance



Run 1D

- We mechanically tune the resonator to scan over frequency space

The Importance of Noise



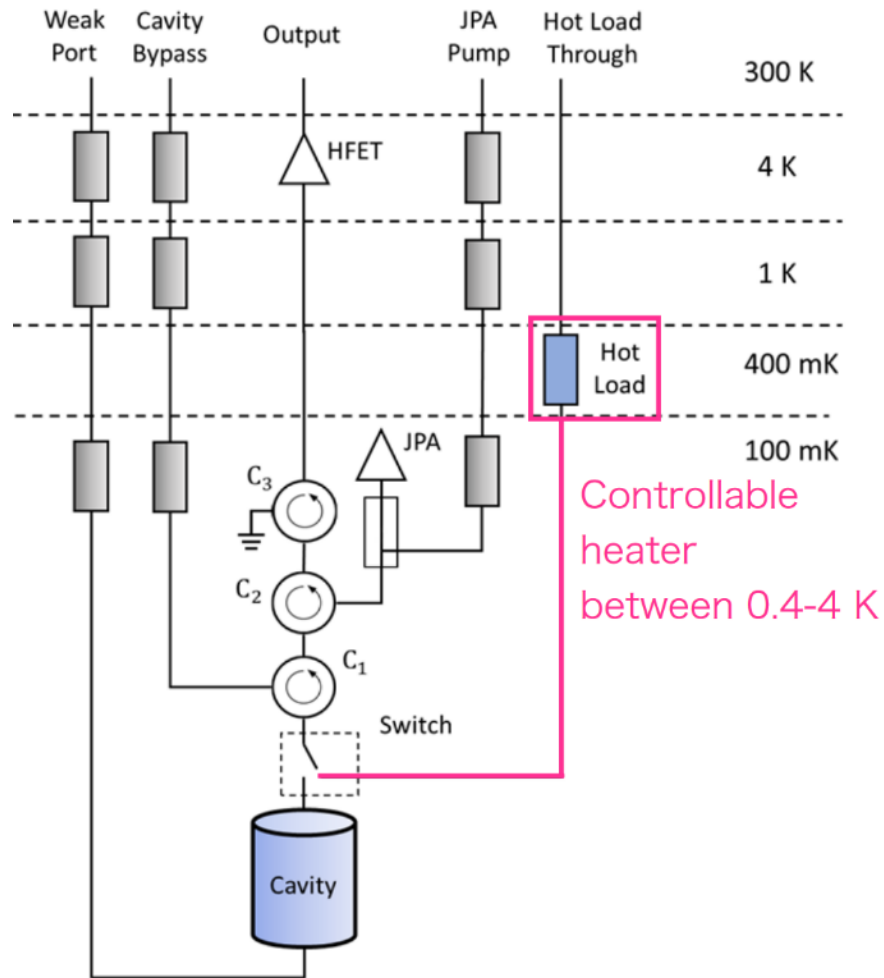
We need our noise to be much smaller than our signal to make a detection.

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

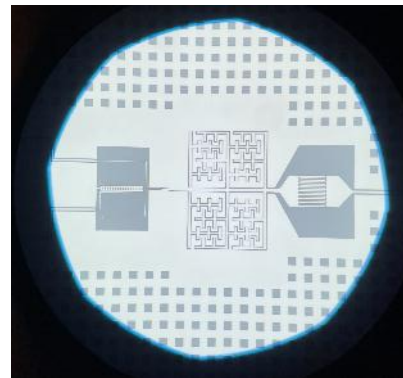
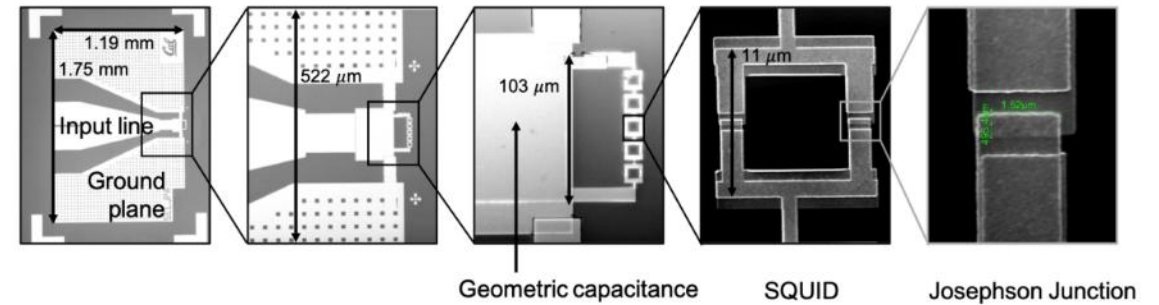
We must carefully calibrate the noise of our system – to understand our sensitivity, we must understand the temperatures of the components, the signal loss in the cables, and the performance of the amplifiers.

Minimizing Noise

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



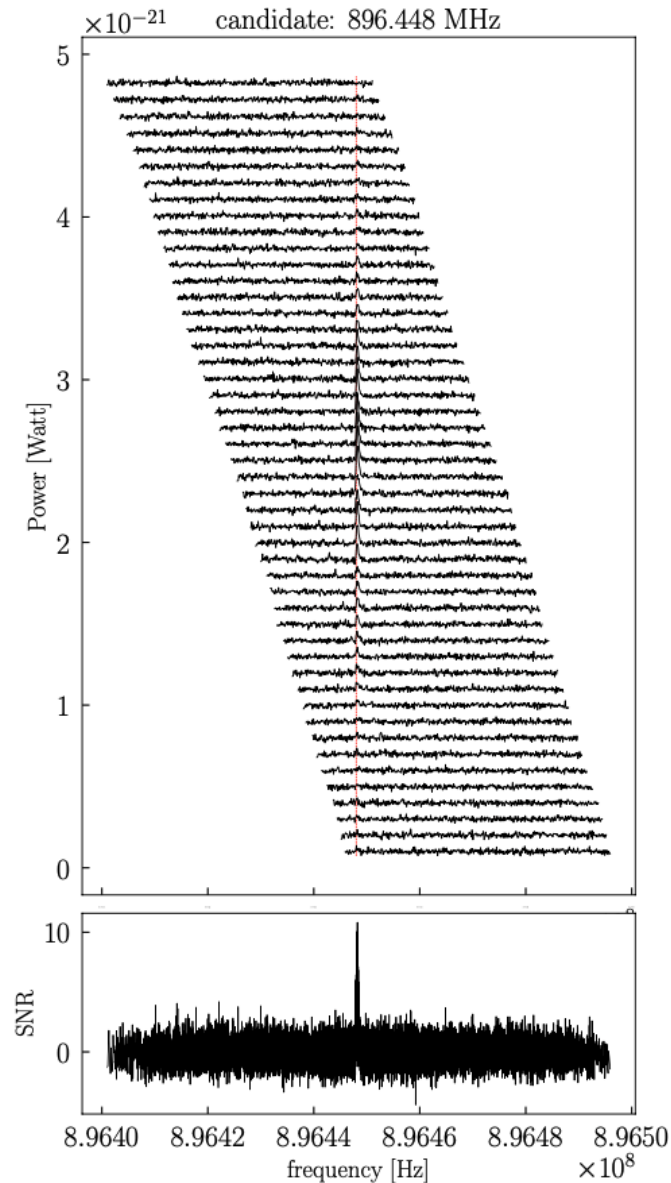
M. Guzzetti, APS April 2023



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

TWPAs Under Test from Lincoln labs, JPL

ADMX Operations

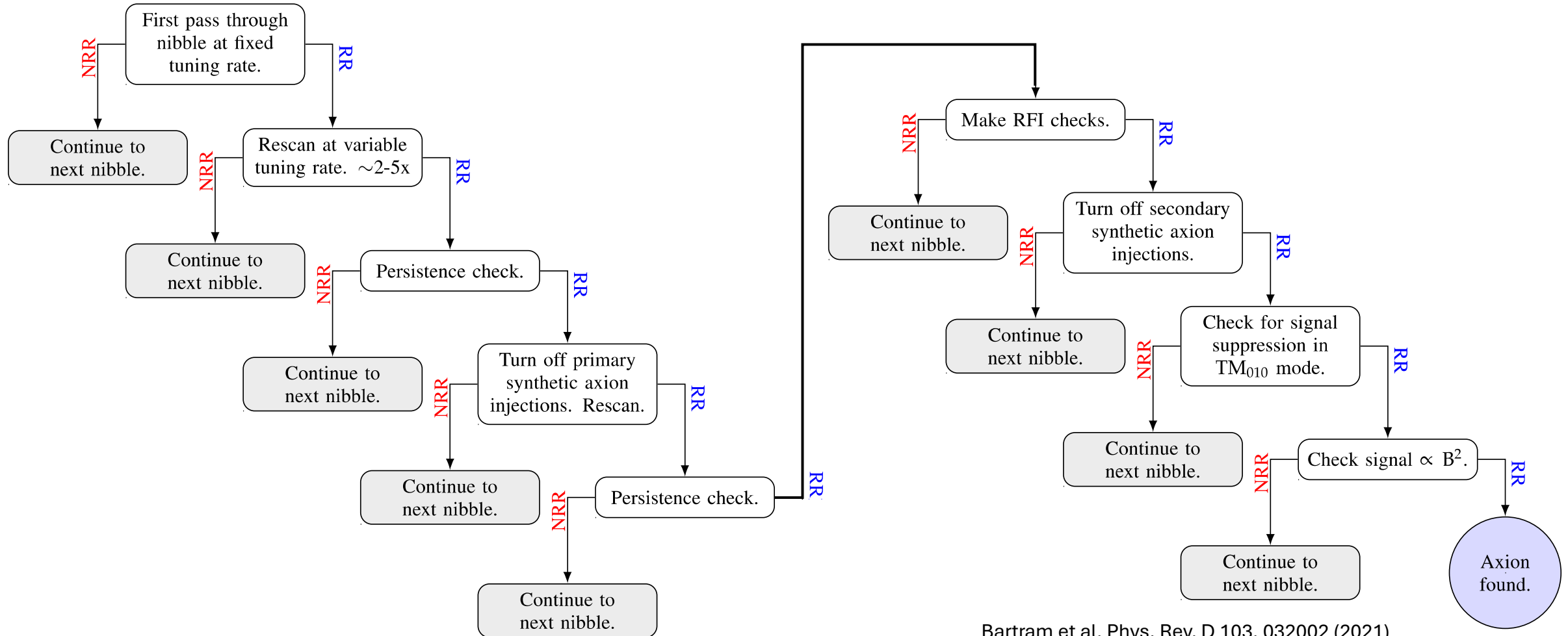


The cavity is tuned every 100 seconds, during which power spectra are taken. Overlapping power spectra are examined for the characteristic axion signal shape appearing on-resonance.

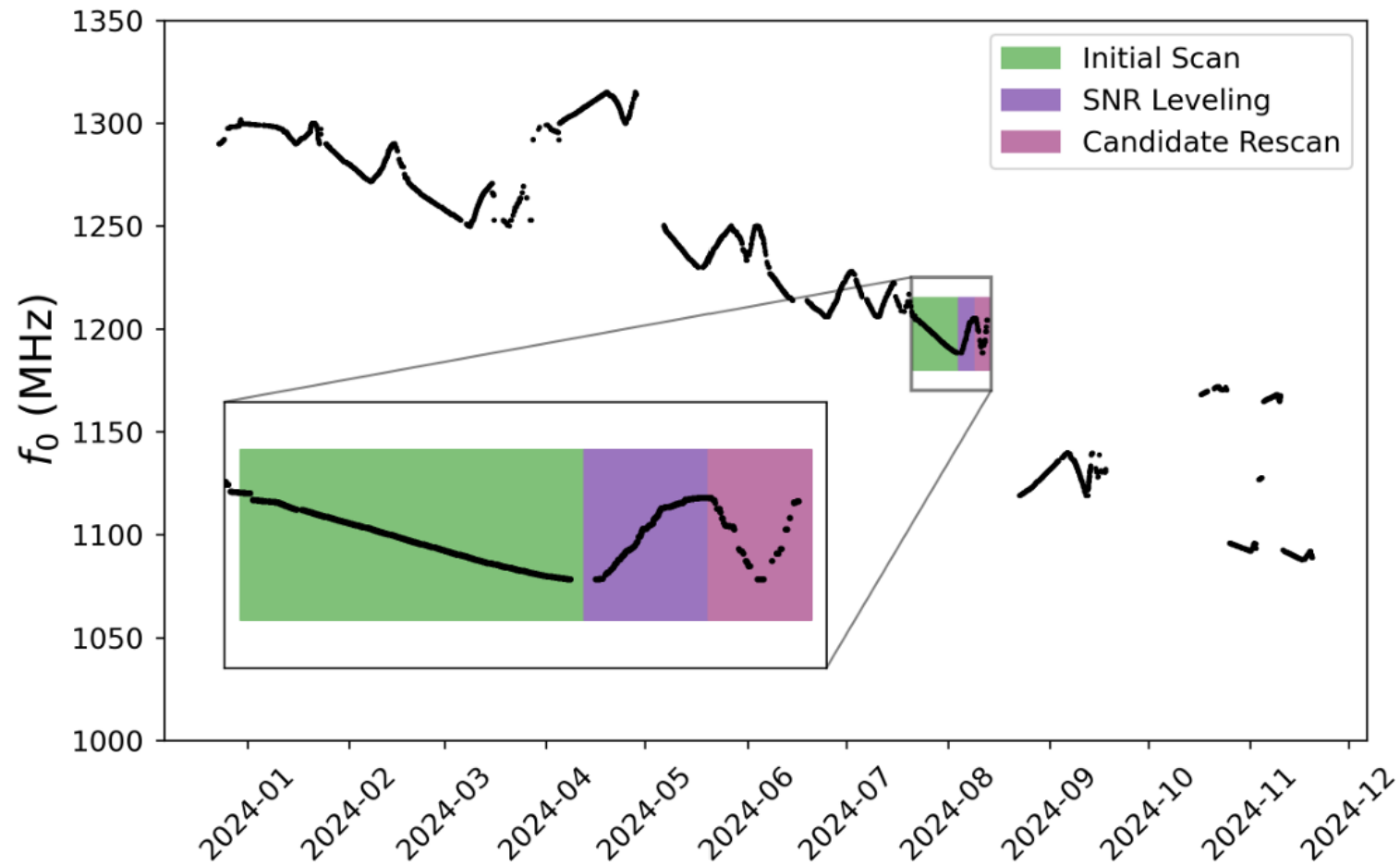
The picture on the left shows how an axion signal would appear in the data. This is a synthetic signal.

Data Taking Cadence

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



Example: ADMX 2024 Operations

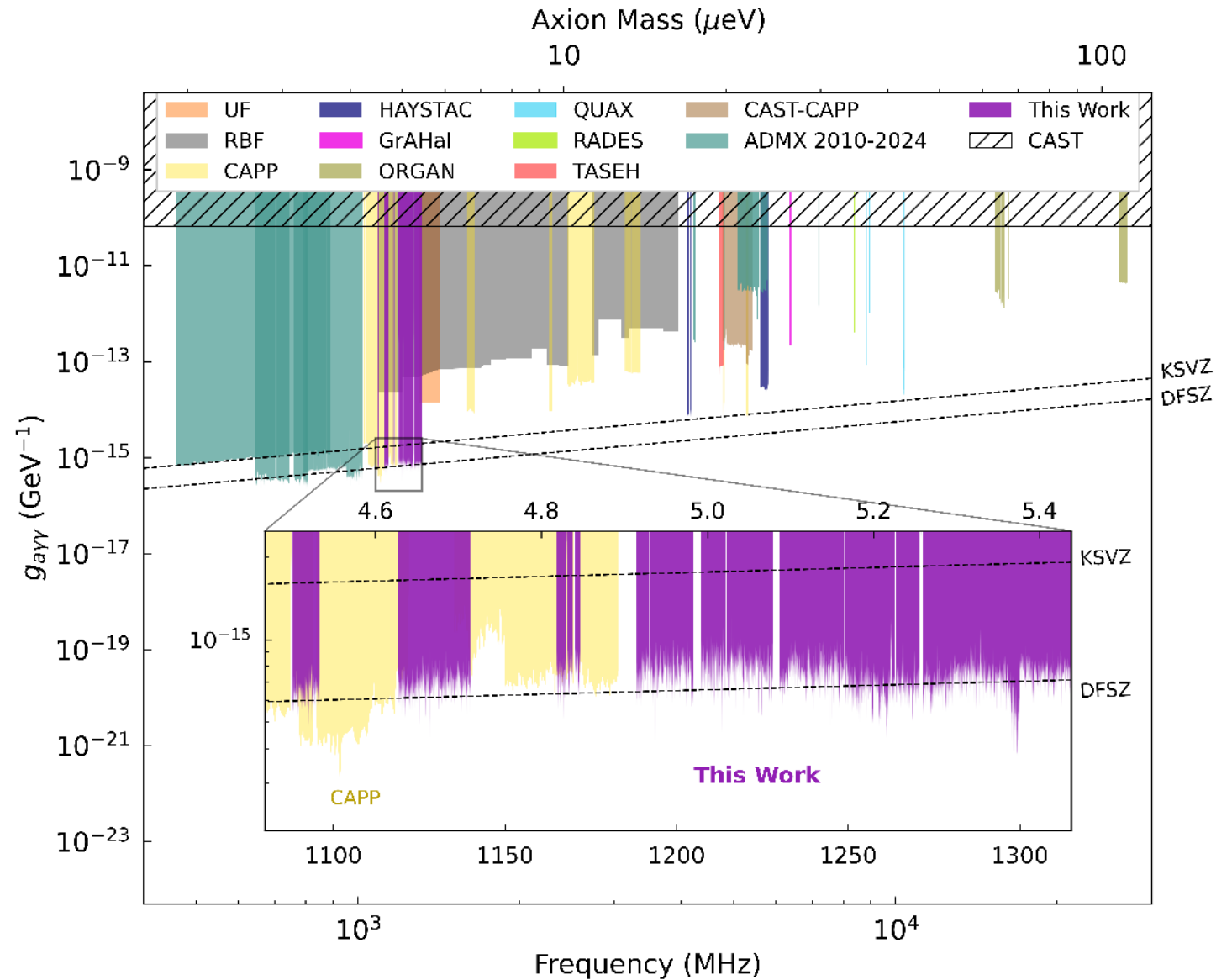


M. Guzzetti, Ph.D. Thesis 2025

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

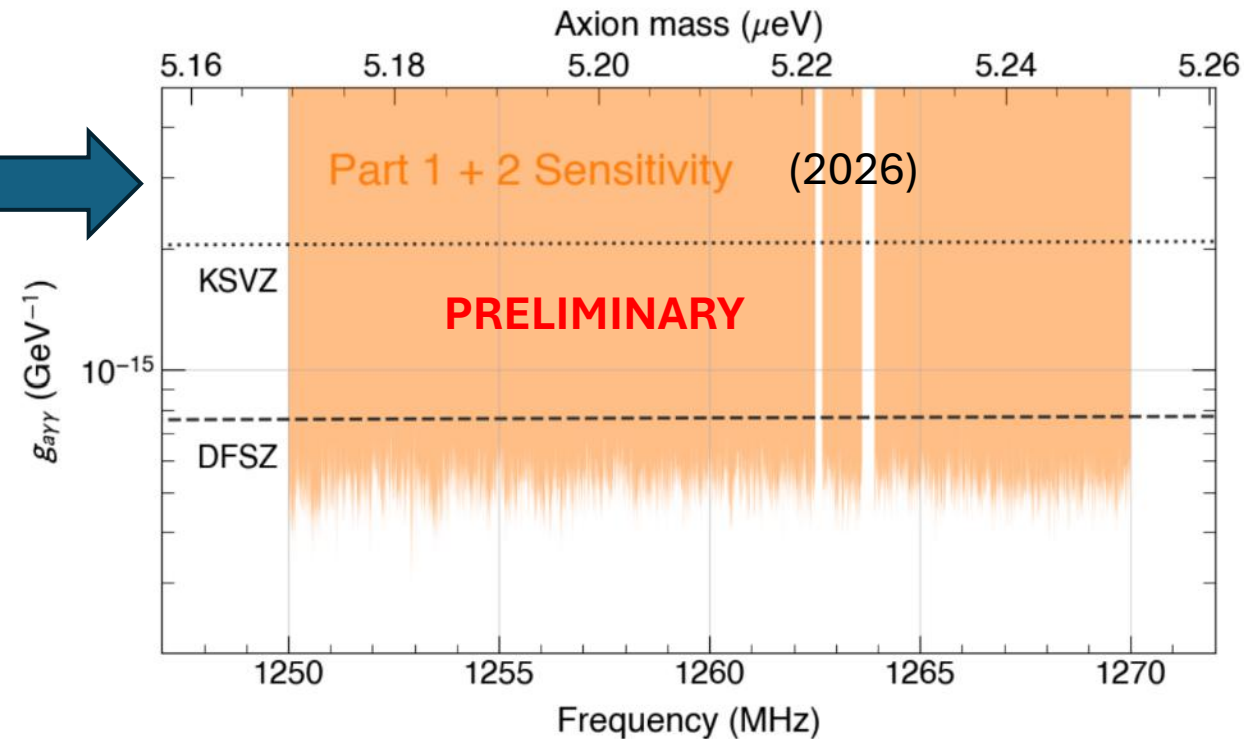
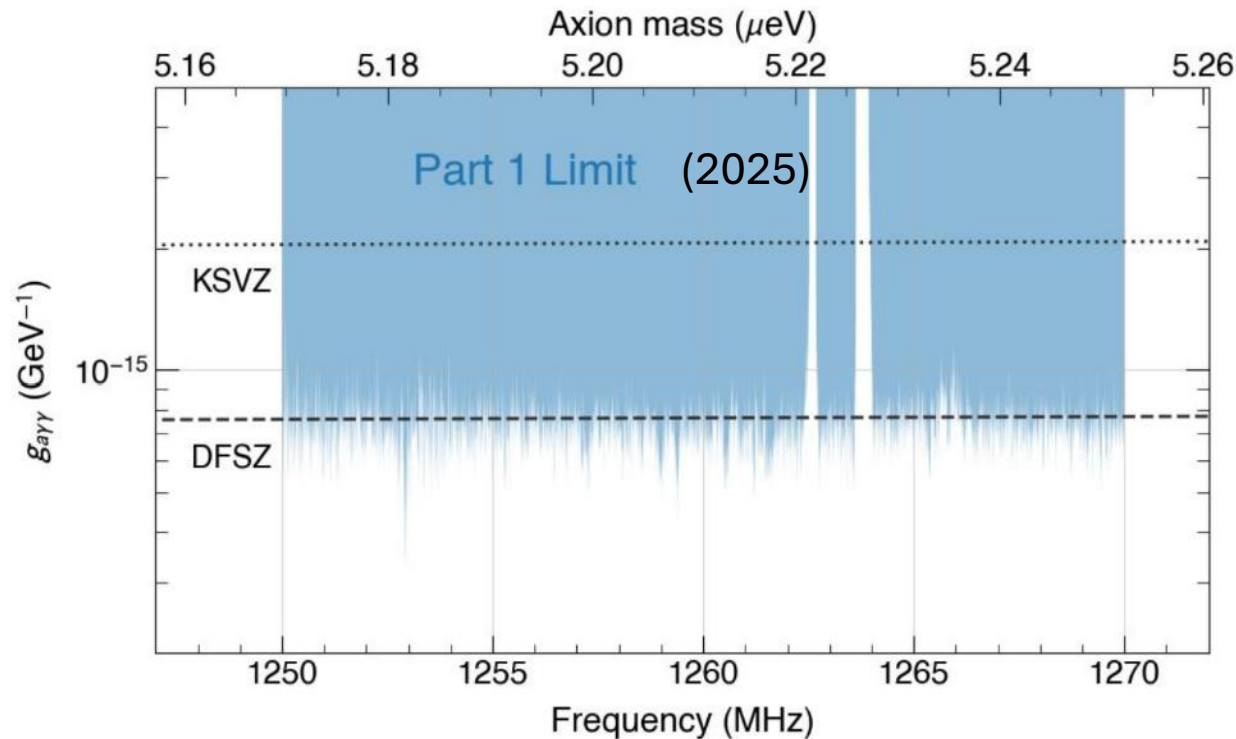
DFSZ Axion Model at
slightly higher densities
excluded



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

ADMX 2026

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

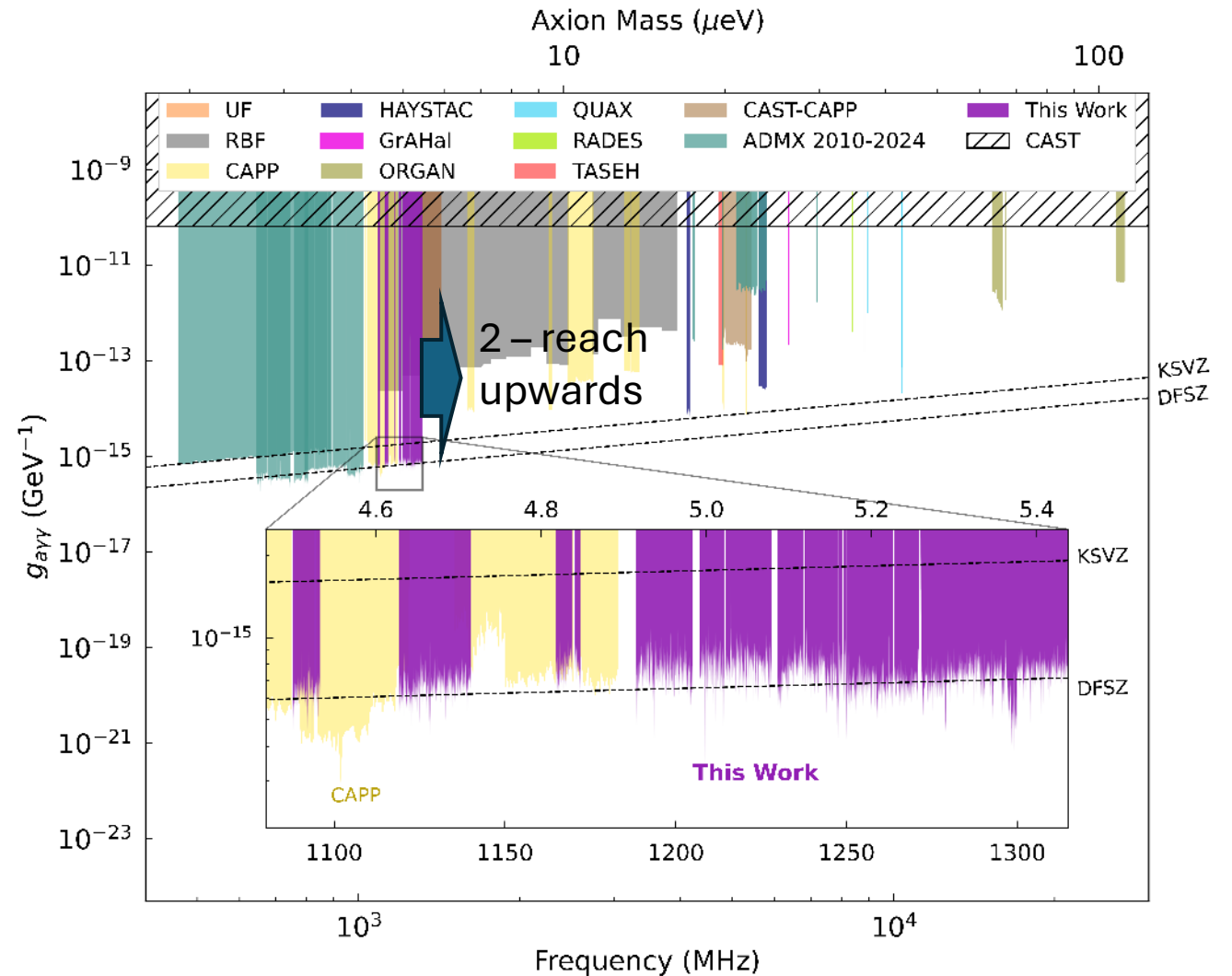


ADMX Near Future

Beyond next year:

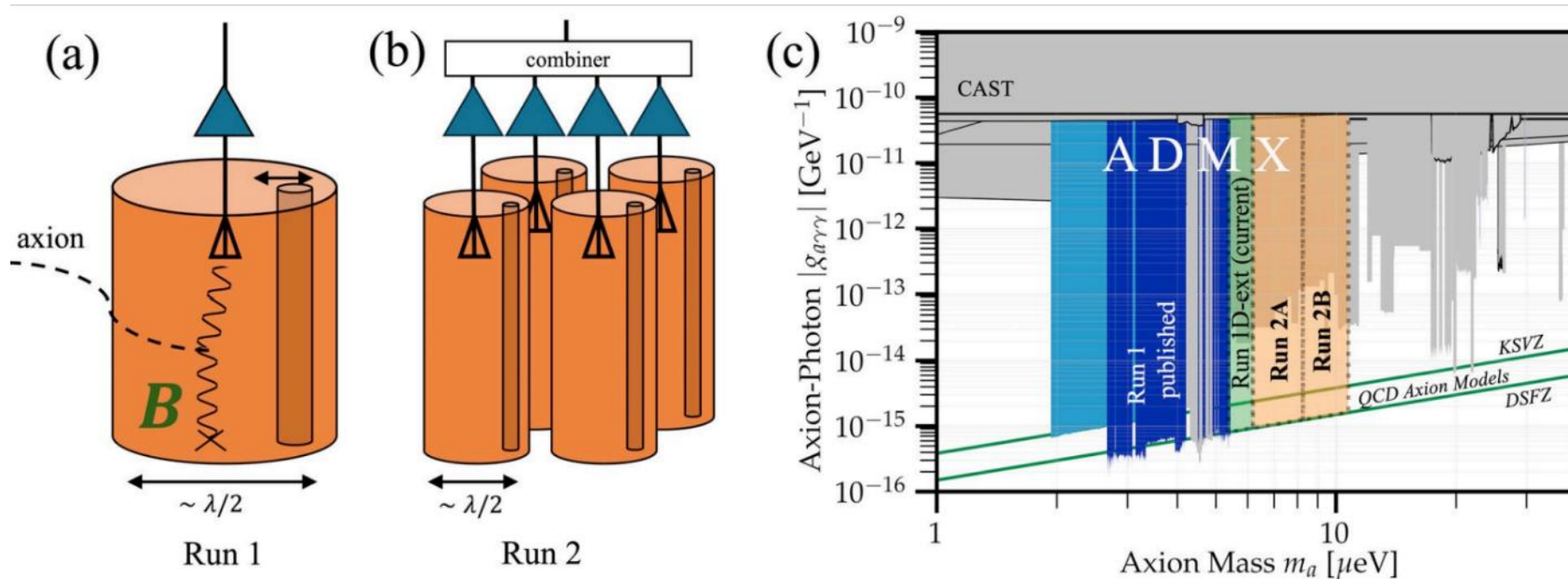
Goal: Extend sensitivity to higher masses using a multicavity system

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



The Future of Haloscopes

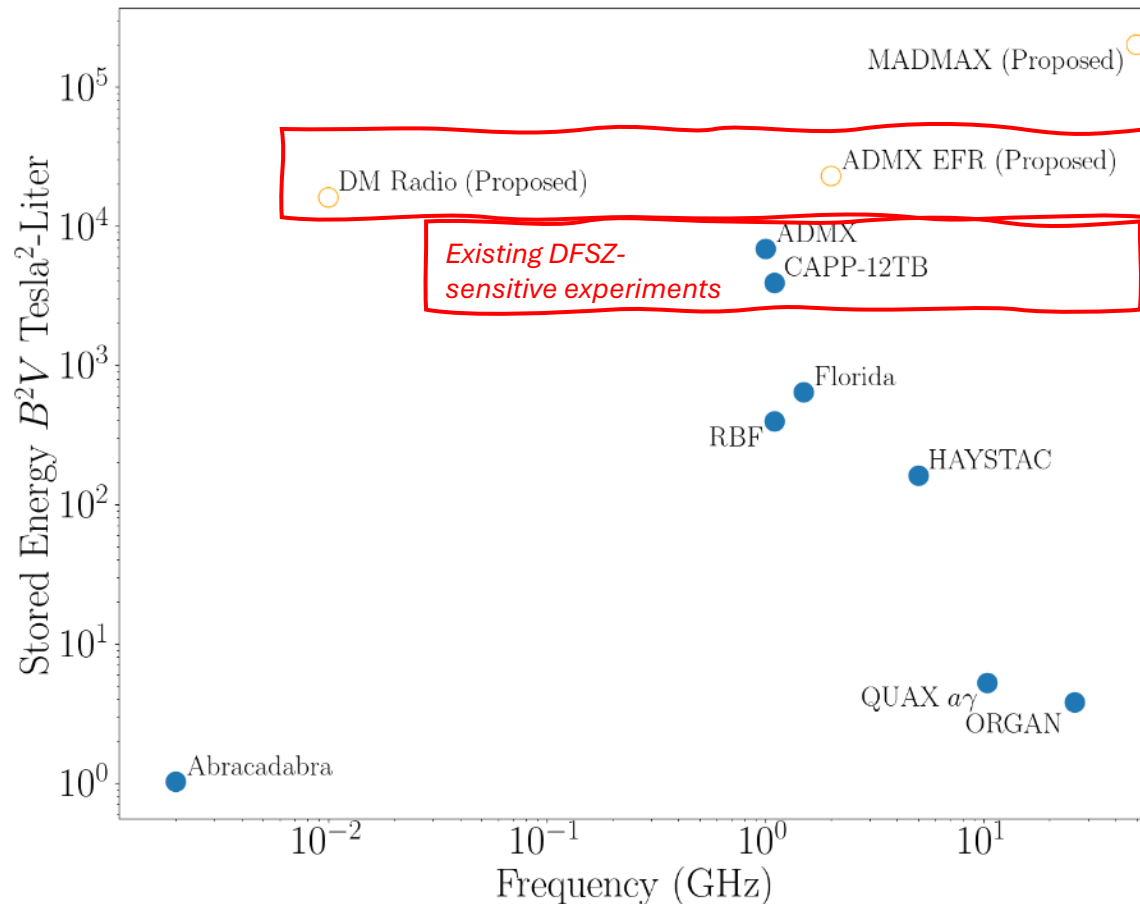
At higher frequencies, axion haloscopes suffer from unfavorable

- 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

Haloscope Magnet Development

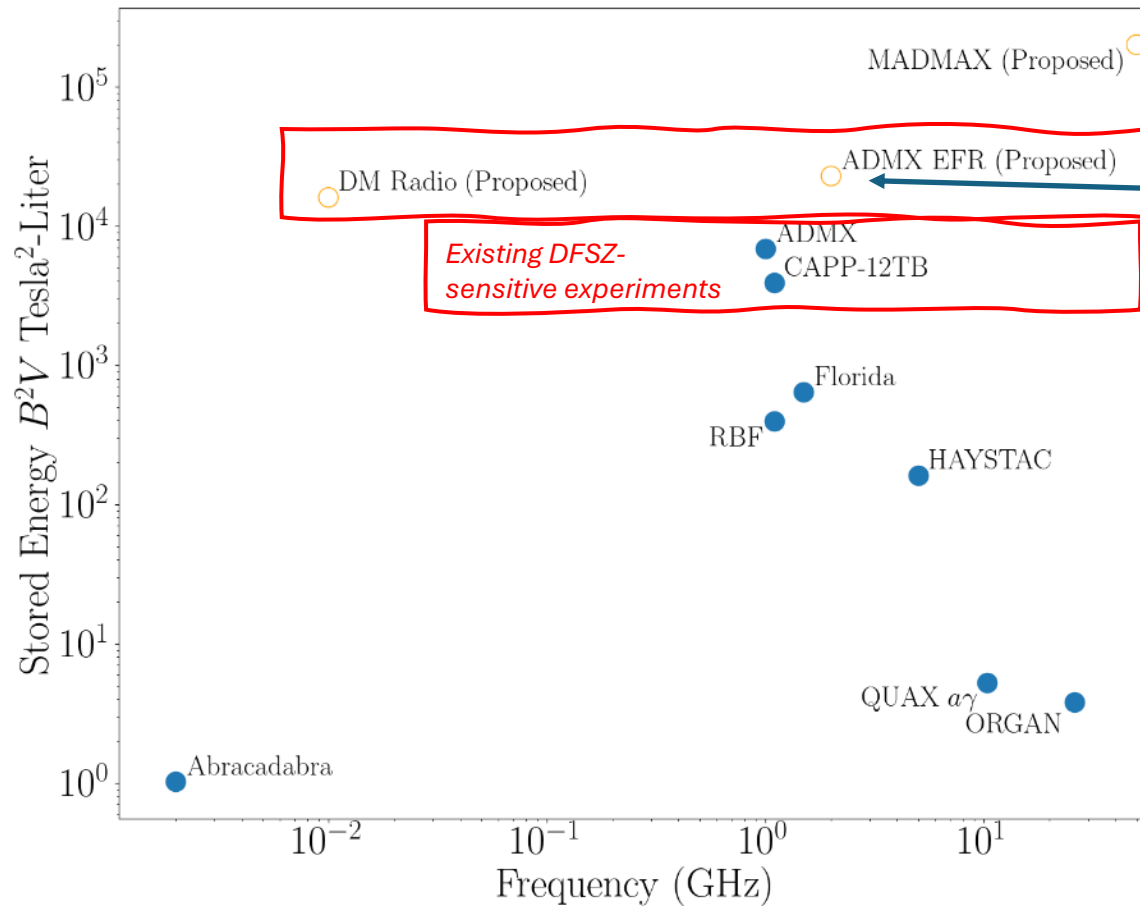


Axion sensitivity scales as magnet stored energy, and scan speed scales as the square of stored energy.

Magnets are large, expensive, and critical for most axion search techniques. They are also potentially usable at different frequency ranges with very different detector styles.

Effectively using a magnet's volume requires sophisticated resonators if the bore size does not match the Compton wavelength.

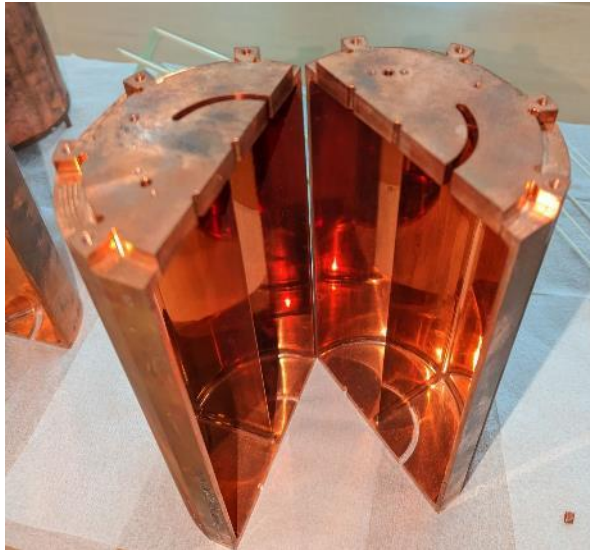
Haloscope Magnet Development



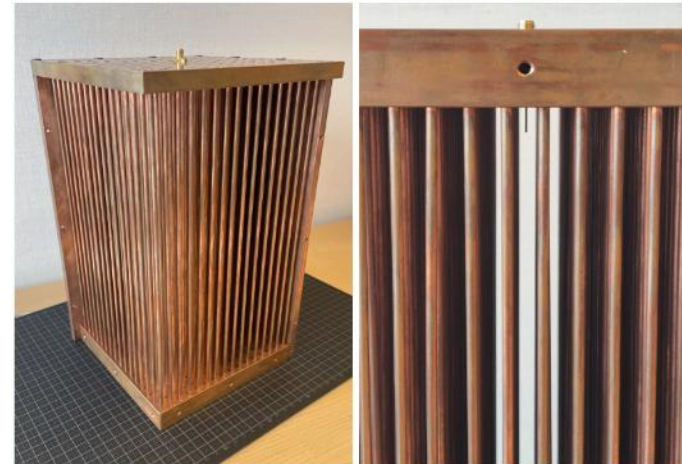
This magnet exists at FNAL.
Other proposed magnets must
be constructed.

Sophisticated Resonators – Multiwavelength Cavities

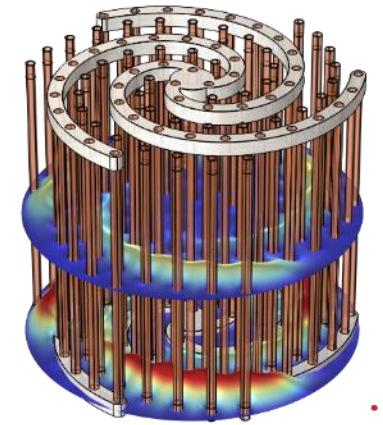
- Dividing single cavities or metamaterial structures captures similar volume gains to multiple cavities



“Pizza” Cavity is divided into subregions and read out coherently.
S. Youn, CAPP (2023)

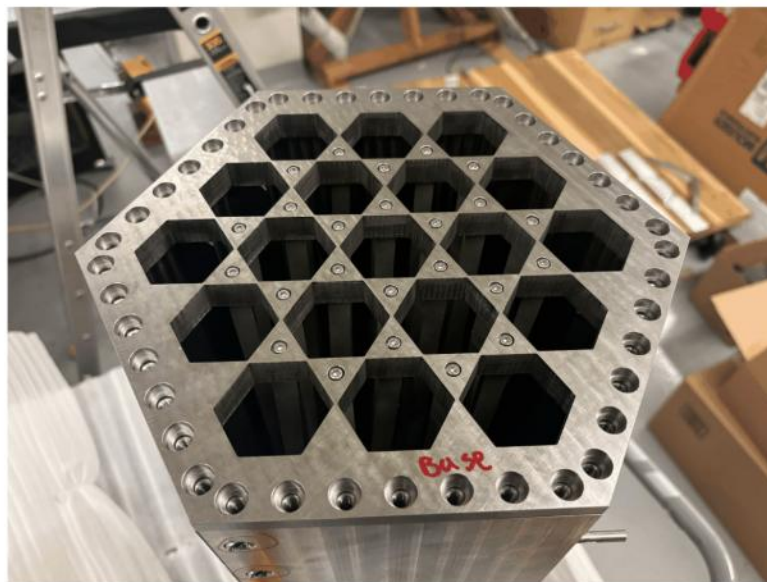
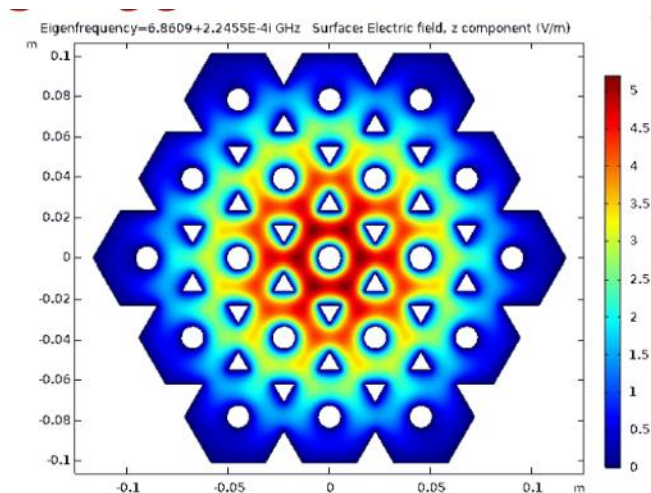


Multiple periodic conductors allow the ALPHA “Plasma Haloscope” to have a multiwavelength volume
A. Millar Phys. Rev. D. 107 055103 (2023)



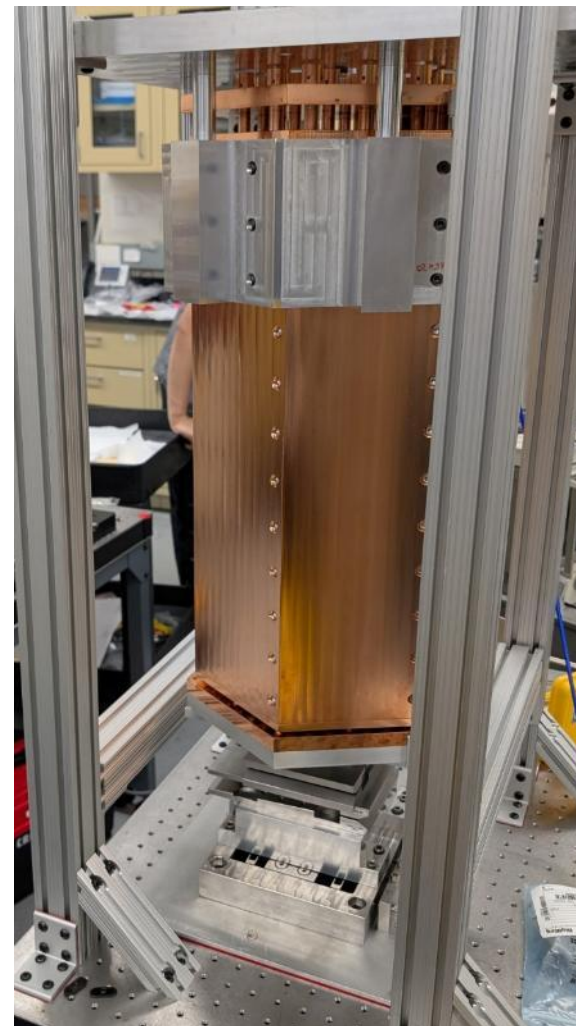
See also:
Lindahl et al. Phys. Rev. Applied 25, 024073 (2026)

Sophisticated Resonators – Multiwavelength Cavities



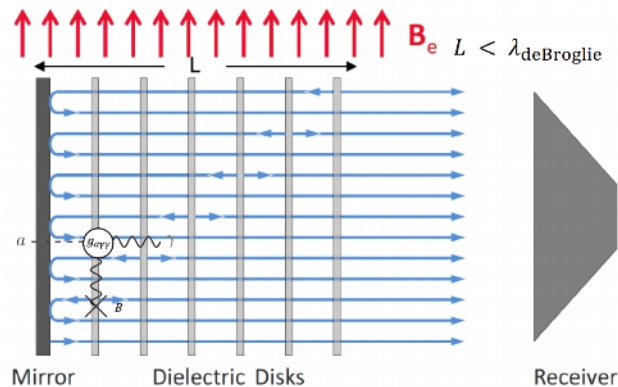
The ADMX beehive-style design is under study for future use in the ADMX magnet as a volume-efficient, tunable way to reach higher frequencies with good sensitivity.

M.O. Withers & C.L. Kuo Phys. Rev.
D 111, 072011 (2025)

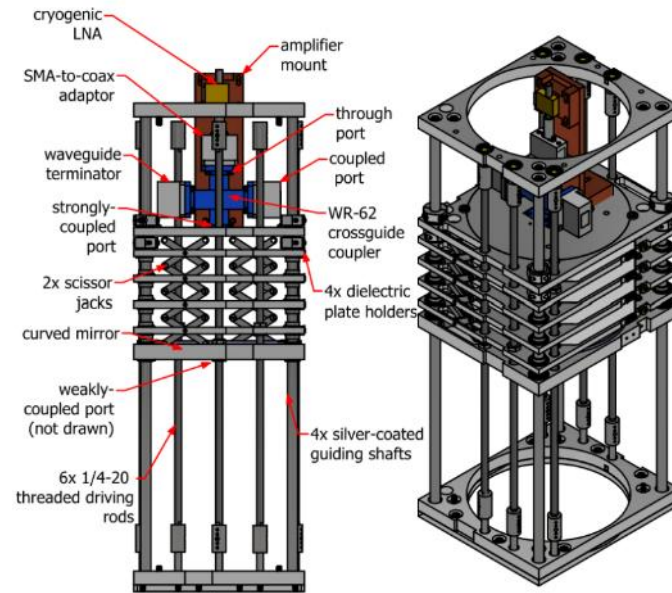


Sophisticated Resonators –Multiwavelength Dielectric Cavities

- Even more complicated designs are under study



MADMAX Design
E. Garutti, Patras
2023



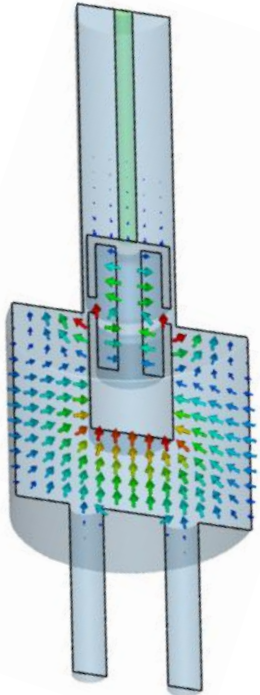
ADMX-Orpheus Design
R. Cervantes, Phys. Rev. D
106, 102002 (2022)



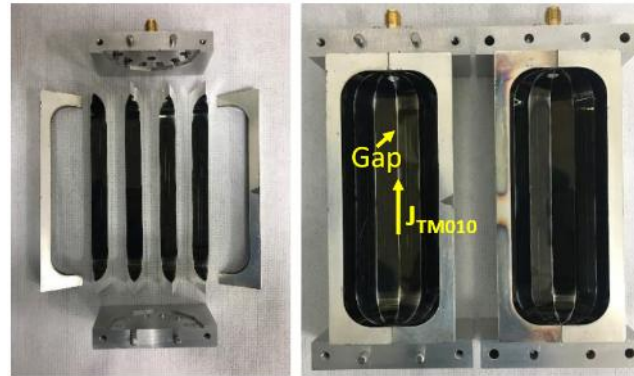
ADMX-VERA wedge-cavity design
T. Dyson, Patras 2023

Sophisticated Resonators – High-Q Resonators

- One thought a pipe dream, groups are developing the capability to run superconducting magnets in multi-Tesla fields



SQMS at Fermilab
reports tunable NbSn
cavity with Q of 10^7
-R. Cervantes, Patras
2025



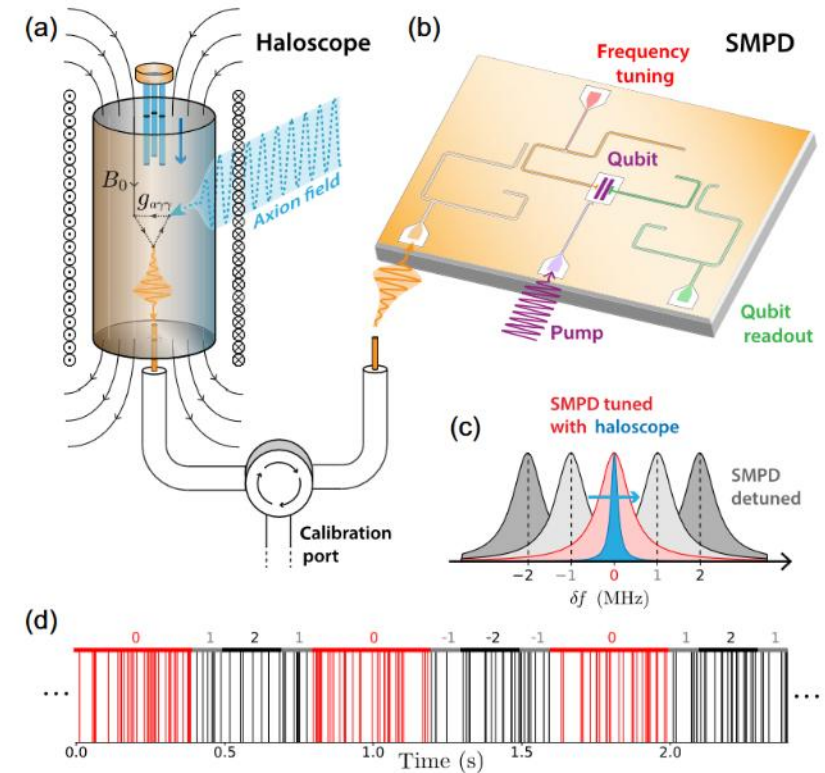
Test NbSn tuning rod (from
SQMS) being installed in
ADMX “sidecar” system
-T. Braine 2025

CAPP reports a Q
of 10^7 with high-Tc
Superconductor
-D. Ahn, Patras
2023



Sub-Quantum-Limited Readout

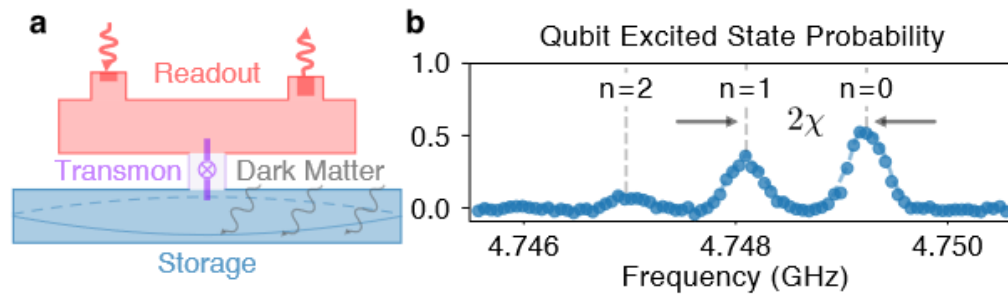
- The standard quantum noise limit (SQL) scales with frequency (~ 30 mK/GHz), so higher frequency axion searches have worse noise.
- The SQL only holds for linear amplification though, so new microwave detectors can evade this



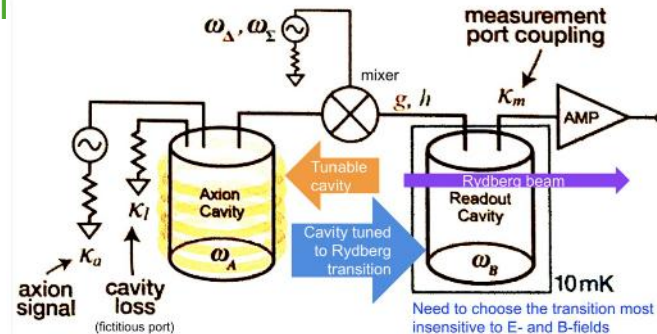
Single microwave photon counters evade the SQL
Braggio et al, PRX 15, 021031 (2025)

See also work by O. Wen,
SLAC

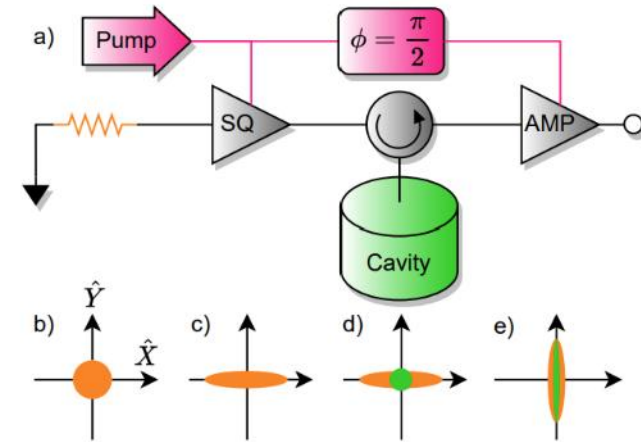
More sub-Quantum Limited Readout



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



Rydberg atoms can be used as microwave photon counters – See CARRACK experiment. Figure and new work from (R. Maruyama – Aspen 2022)

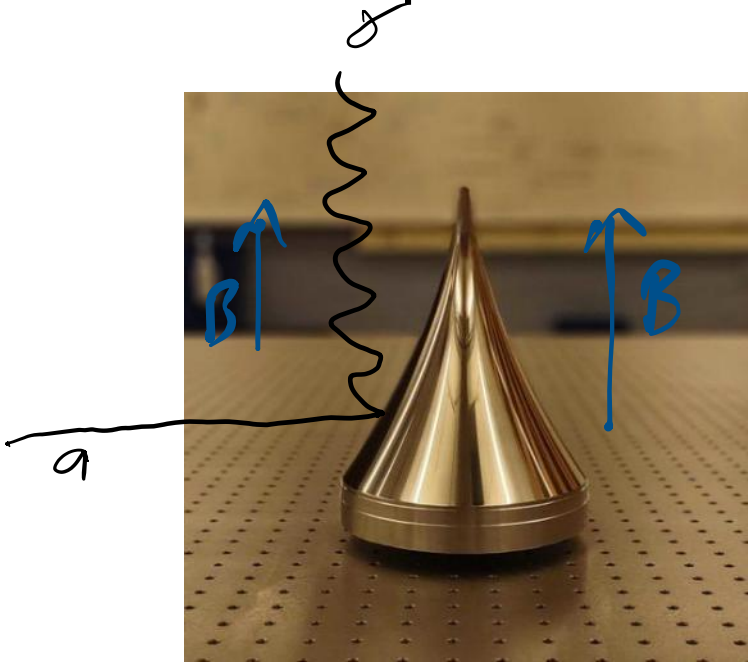


Squeezed noise setup used in HAYSTAC experiment
Jewell et al. 2301.09721 (2023)

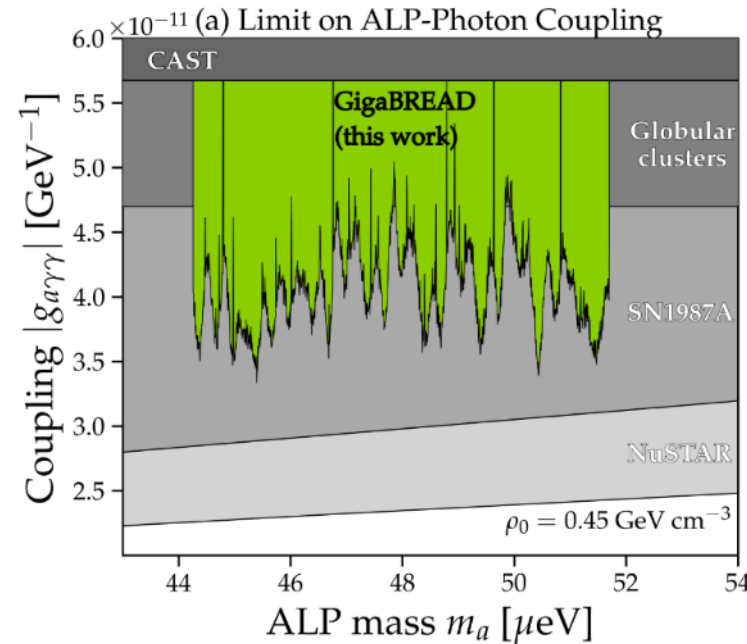
See also CEASEFIRE – Wurtz et al. PRX 2,040350 (2021)

Beyond the Cavity Haloscope – Higher Frequencies

- At the highest frequencies, nonresonant axion conversion at metal or dielectric boundaries can make a ‘dish antenna’ axion search.
- Example: the BREAD experiment focuses converted photons with a cone-shaped emitter.



My sketches on image from S. Knirck



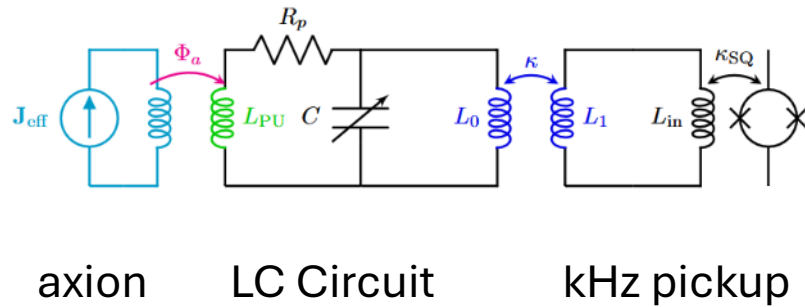
For even higher frequencies, see
Disordered Dielectrics
Koppell et al Phys. Rev.
D 113, 083045 (2026)

Axion limits from GigaBREAD prototype
Hoshino et al. Phys Rev Lett 134, 171002 (2025)

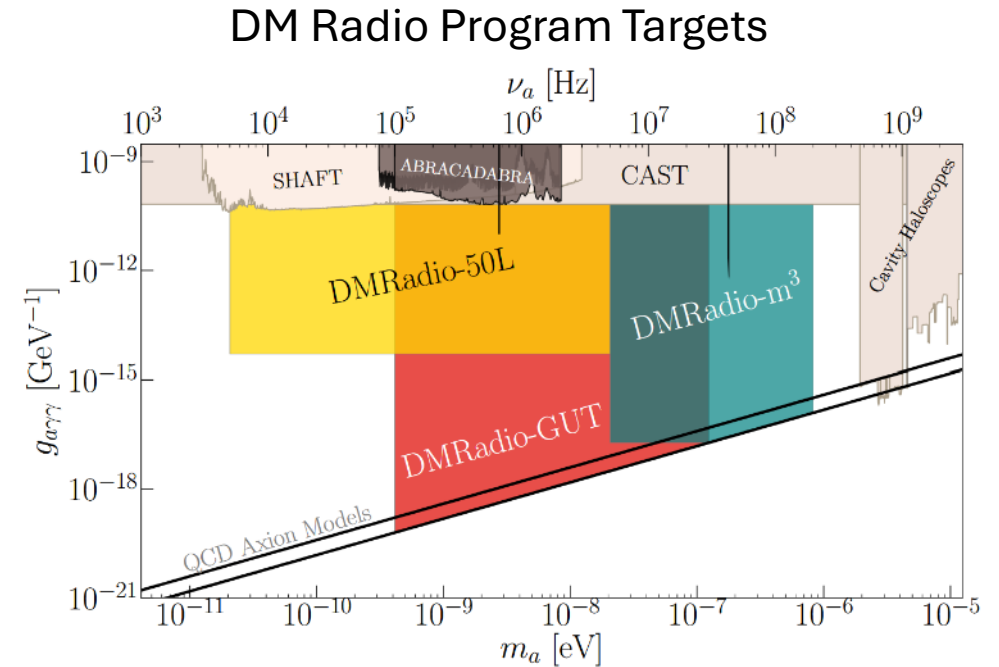
Rybka - UGRP Tokyo 2026

Below the Cavity Haloscope – Lower Frequencies

- Non-geometric resonators (LC-circuits) can replace the cavity of a haloscope to access lower frequencies.
- Example: DM Radio (Brouwer et al. Phys. Rev. D 106, 103008 2022)



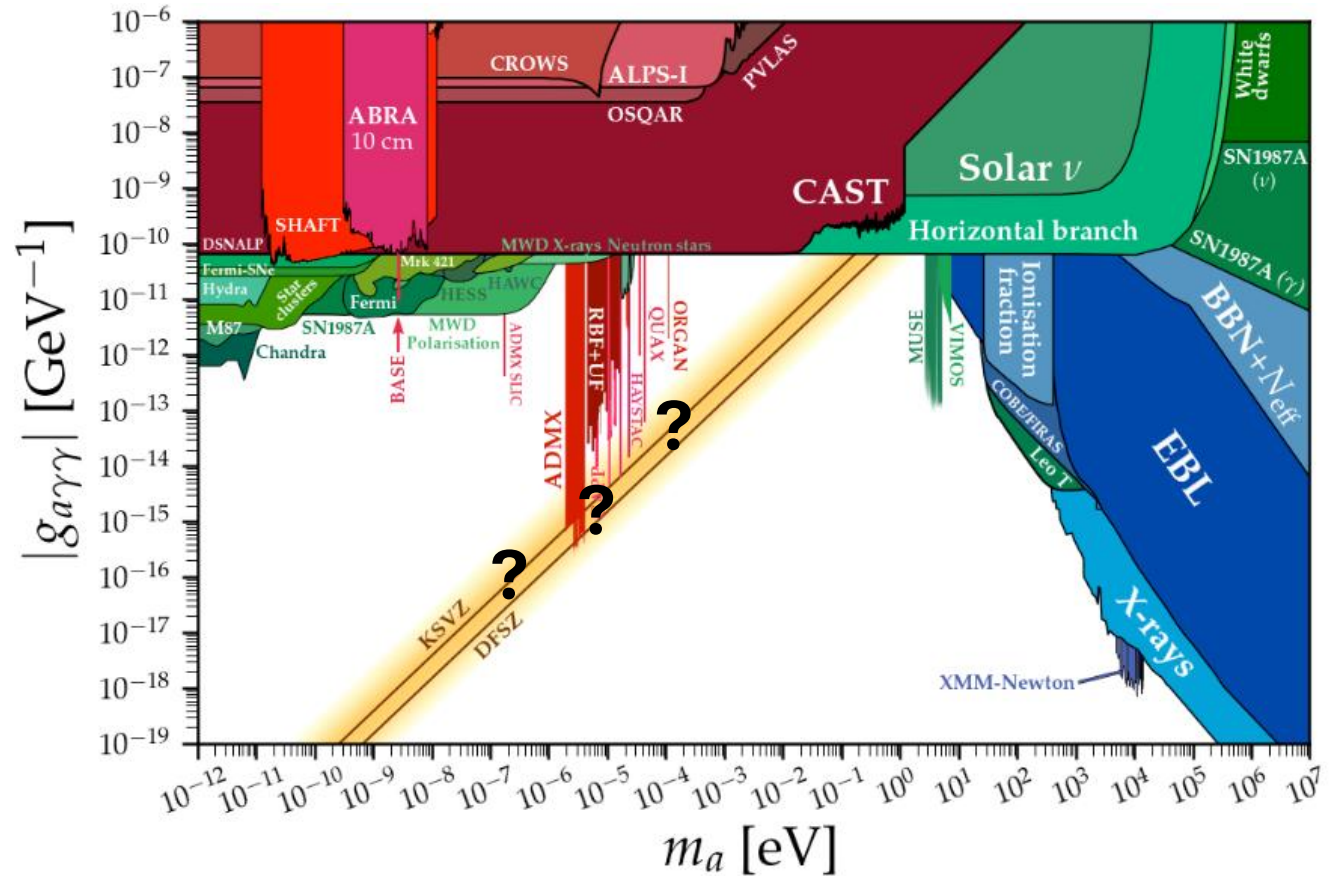
For another low-frequency technique, see
RF Haloscopes Ex: Berlin et al JHEP 2020,
88 (2020)



Rapidis Patras 2025

Consequences of Discovery - Particles

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



Conclusions

- Axions are a compelling dark matter candidate, but so far a very small range has been explored
- Experiments like ADMX are underway searching promising axion parameter space
- New technologies are rapidly improving sensitivity and frequency coverage
- This is a fast-moving, exciting field of dark matter experiment