Pacific Northwest NATIONAL LABORATORY

ADMX AXION DARK MATTER EXPERIMENT

Current Status of the Axion Dark Matter eXperiment

10th Symposium on Prospects in the Physics of Discrete Symmetries (DISCRETE)

November 17, 2026
Comenius University Bratislava, Slovakia

Thomas Braine

PNNL Researcher

On Behalf of the ADMX Collaboration

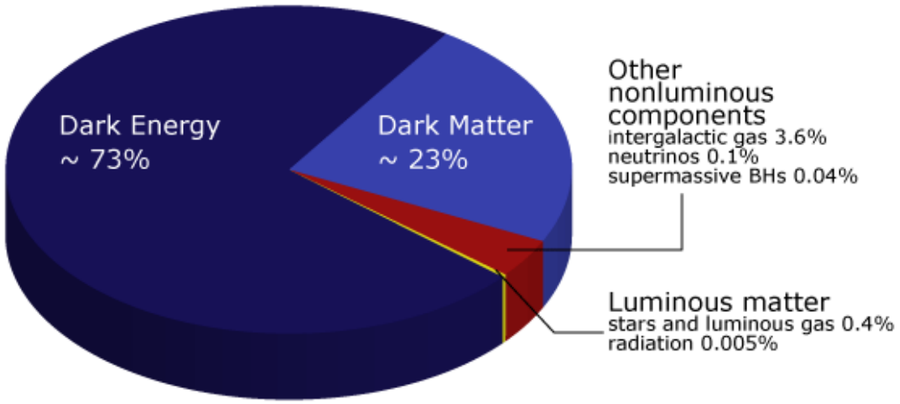


U.S. DEPARTMENT of ENERGY BATTELLE

PNNL is operated by Battelle for the U.S. Department of Energy

What is Dark Matter?

- Must be ‘cold’/slow enough to seed galaxy structure formation
- Pretty sure it can’t be baryonic…
  - deuterium and lithium abundance
  - backlighting and microlensing
- Interacts with photons feebly enough to evade detection so far!





Bullet Cluster – NASA JWST Chandra Composite

Dark Matter	???
Feebly-interacting with photons	
Gravitationally interacting	
Non-baryonic	
Very stable	
Cold (non-relativistic)	
Generated in abundance in early universe	

Another Problem: Strong CP

- Strong force Lagrangian contains a CP-violating term in Standard model
- Implies measurable neutron electric dipole moment (EDM).

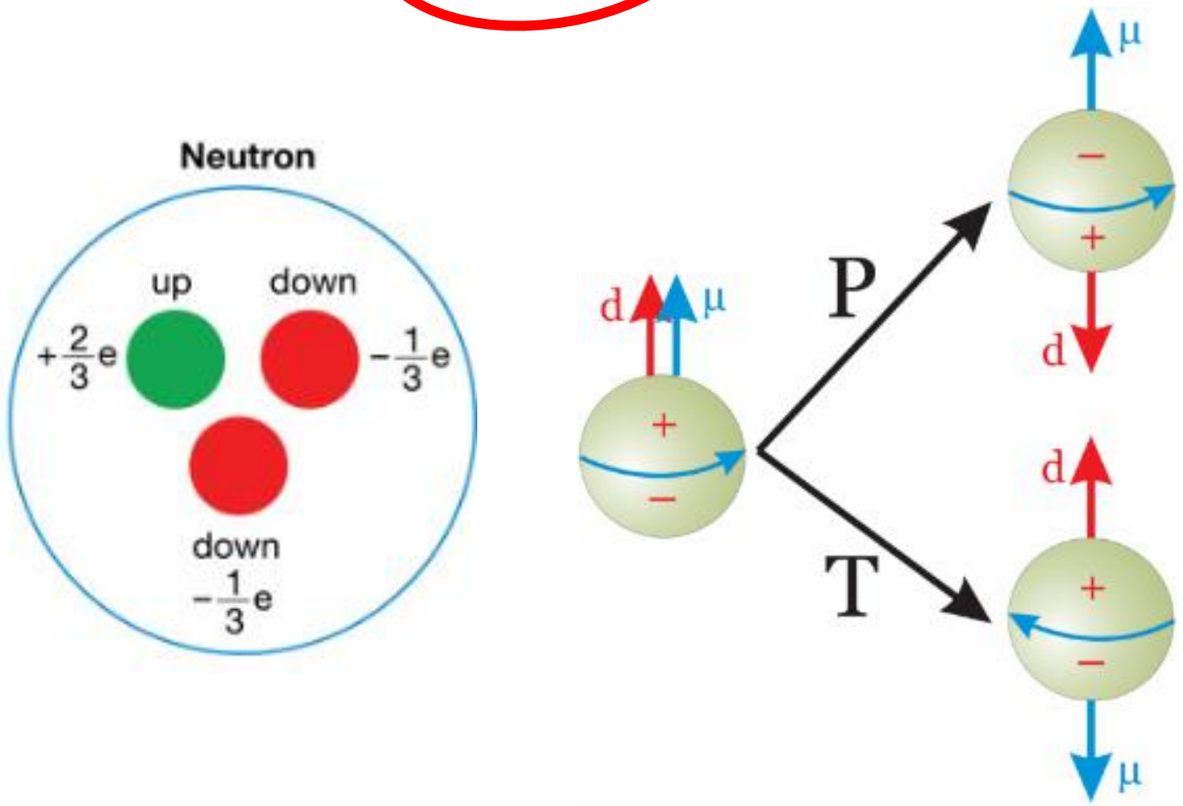
$$d_{n,SM} = (5.2 \times 10^{-16} e \cdot cm)\bar{\theta}$$

- Experiments constrain the neutron EDM close to zero implying CP conservation ($\bar{\theta} < 10^{-10}$)[2]

$$d_{n,exp} = (0.0 \pm 1.1_{stat} \pm 0.2_{sys}) \times 10^{-26} e \cdot cm$$

- Fine Tuning Problem
- "Everything not mandatory, is compulsory" –Murray Gell-Mann (1956?)[1]

$$\mathcal{L}_{QCD} = -\frac{1}{4} F_{\mu\upsilon} F^{\mu\upsilon} + \theta \frac{g^2}{32\pi^2} F_{\mu\upsilon} \tilde{F}^{\mu\upsilon} - \bar{\psi}(i\gamma^{\mu} D_{\mu} - m e^{i\theta' \gamma_5})\psi$$



[1] C. Abel et al. Phys. Rev. Lett. 124, 081803 — Published 28 February 2020
[2]Helge, Kragh. https://arxiv.org/ftp/arxiv/papers/1907/1907.04623.pdf

Peccei-Quinn Symmetry

- CP Conservation → New Symmetry
- New global U(1) chiral symmetry spontaneously broken in the early universe
- $\bar{\theta}$ is a dynamical variable which relaxes to zero when symmetry is broken

$$\mathrm{V}(\phi) = \mu^2 \left(|\phi|^2 - {f_{PQ}^2}/{2} \right)^2$$

- Implies the existence of a pseudo scalar boson dubbed the **axion**!

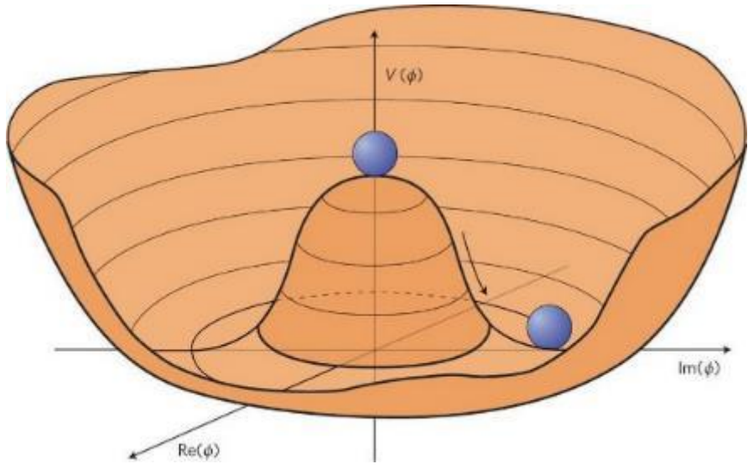
$$m_a \approx 5.691\ \mu eV\ \frac{10^{12}\ GeV}{f_{PQ}},\ g_{a\gamma\gamma} = \alpha \frac{g_\gamma}{\pi f_{PQ}}$$



Roberto Peccei



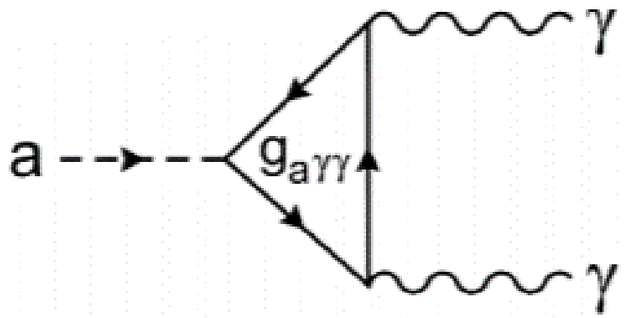
Helen Quinn



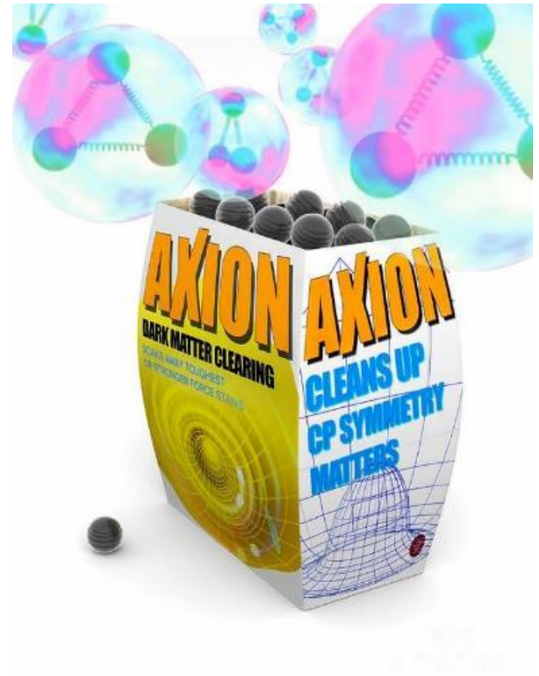
Axion Dark Matter

- Axions give great dark matter characteristics at low m_a!
- Vacuum Realignment mechanism creates abundant cold axion production in the early universe
- Low mass makes it ‘wave-like’ dark matter operating as a coherent, classical field
- Can we detect a faint radio signature from this field?

$$m_a \approx 5.691\ \mu eV\ \frac{10^{12}\ GeV}{f_{PQ}},\ g_{a\gamma\gamma} = \alpha \frac{g_\gamma}{\pi f_{PQ}}$$

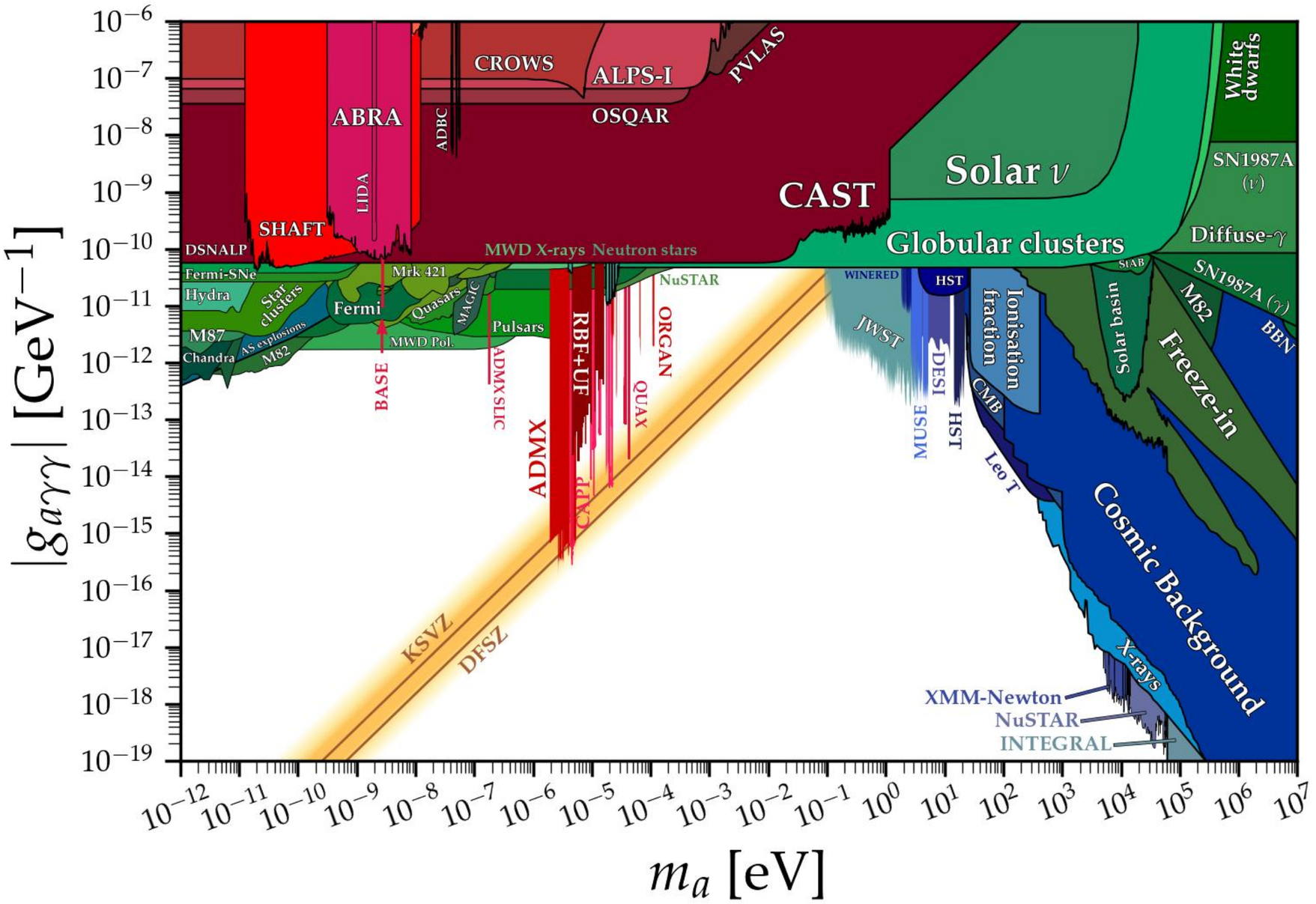


$$\mathcal{L}_{A\gamma\gamma} = -g_{A\gamma\gamma}\boldsymbol{E}\cdot\boldsymbol{B}\phi_A$$

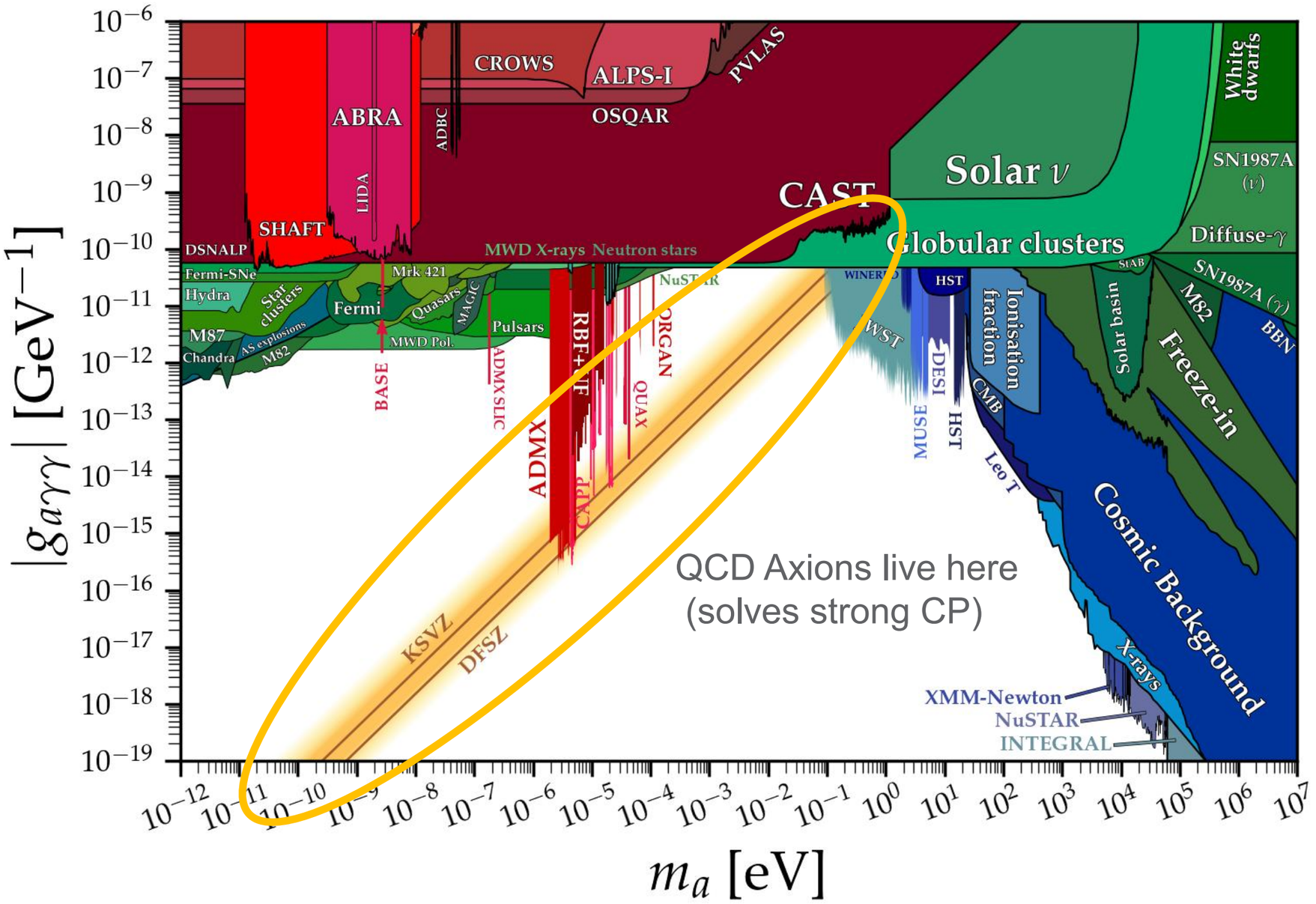


Dark Matter	Axions
Feebly-interacting with photons	✓
Gravitationally interacting	✓
Non-baryonic	✓
Very stable	✓
Cold (non-relativistic)	✓
Generate in abundance in early universe	✓

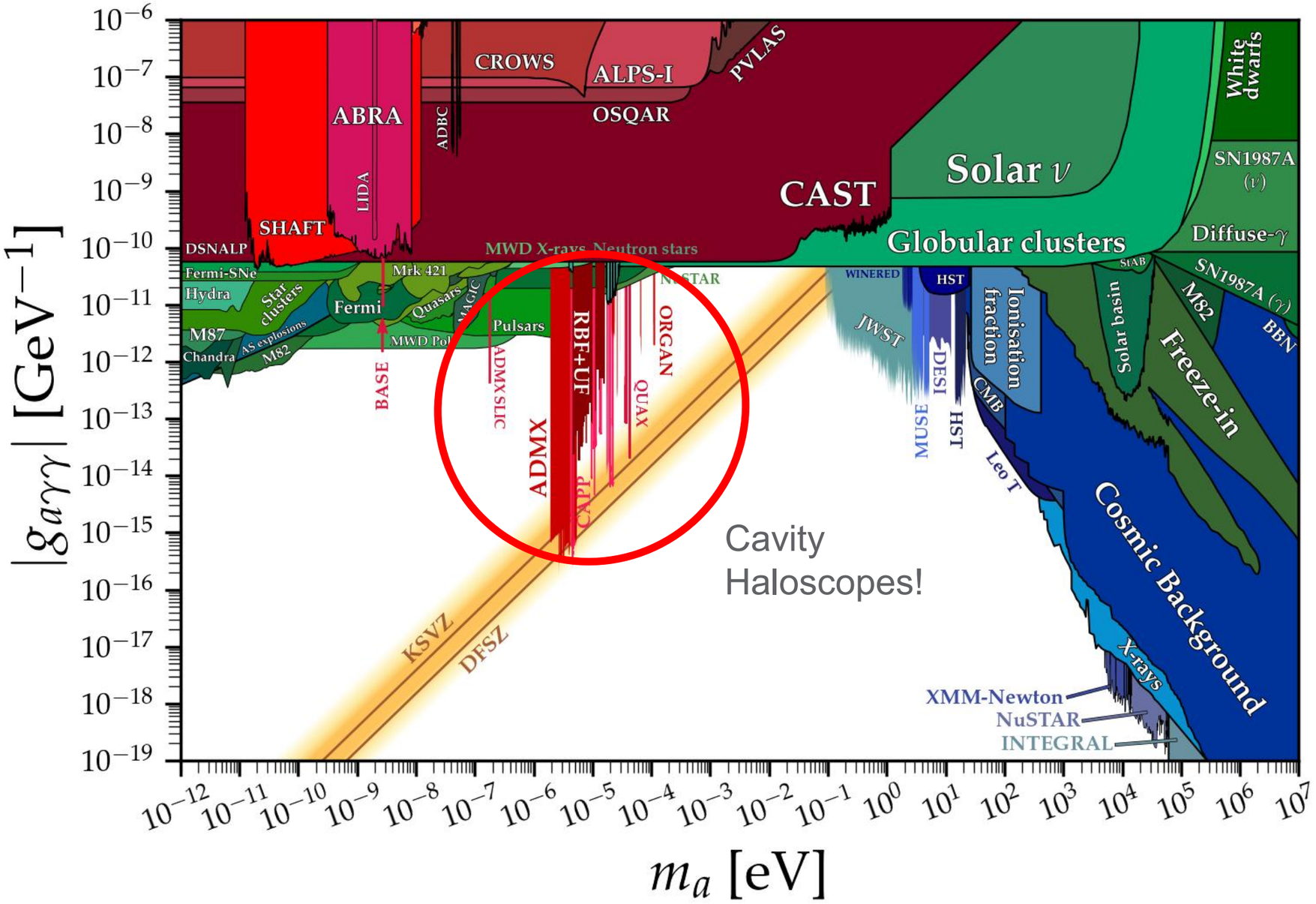
Where have we looked for axions?



Where have we looked for axions?

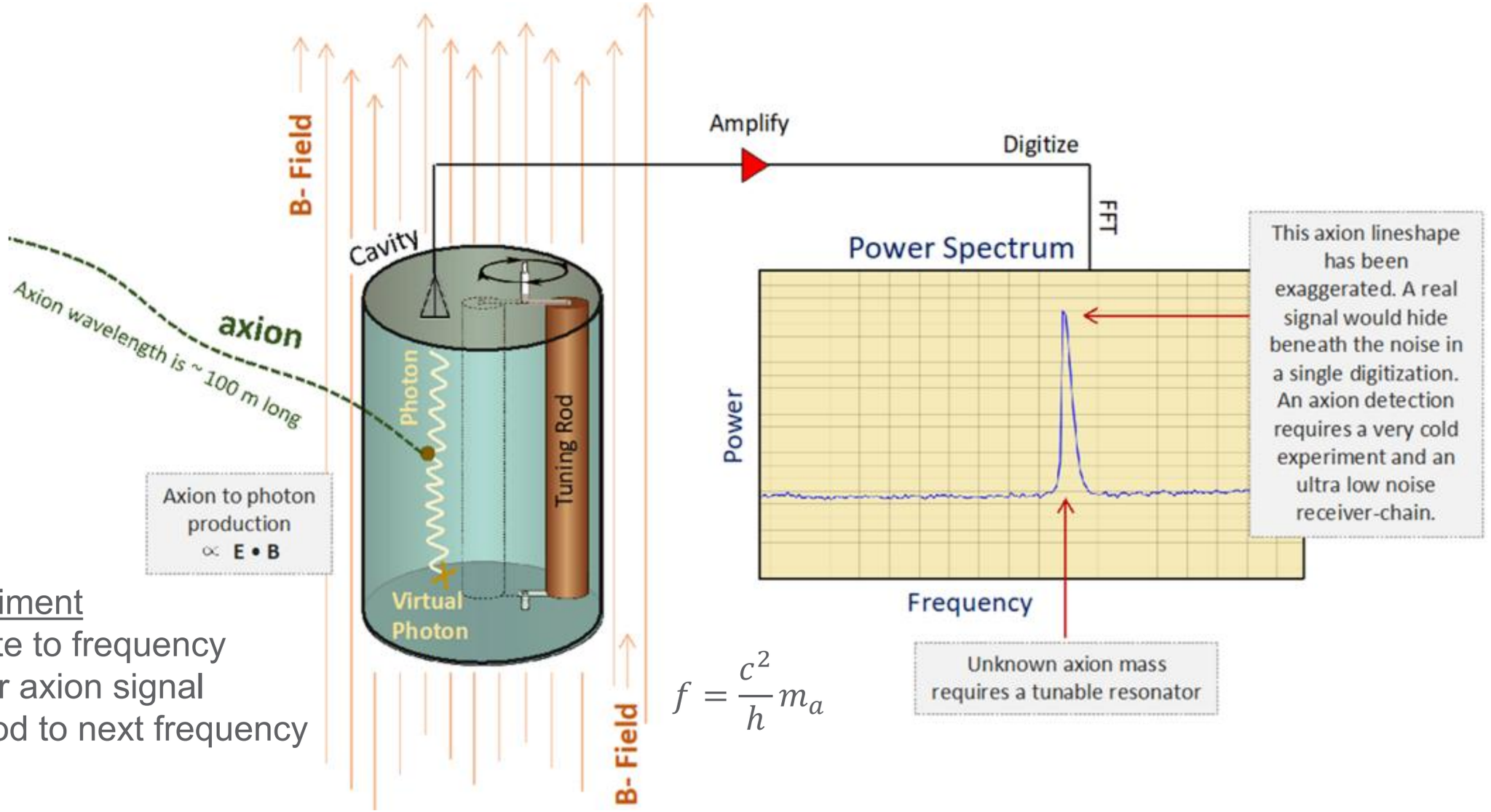


Where have we looked for axions?



Axion Cavity Haloscopes

External Magnetic Field acts as a virtual photon to stimulate photon production from axion DM halo

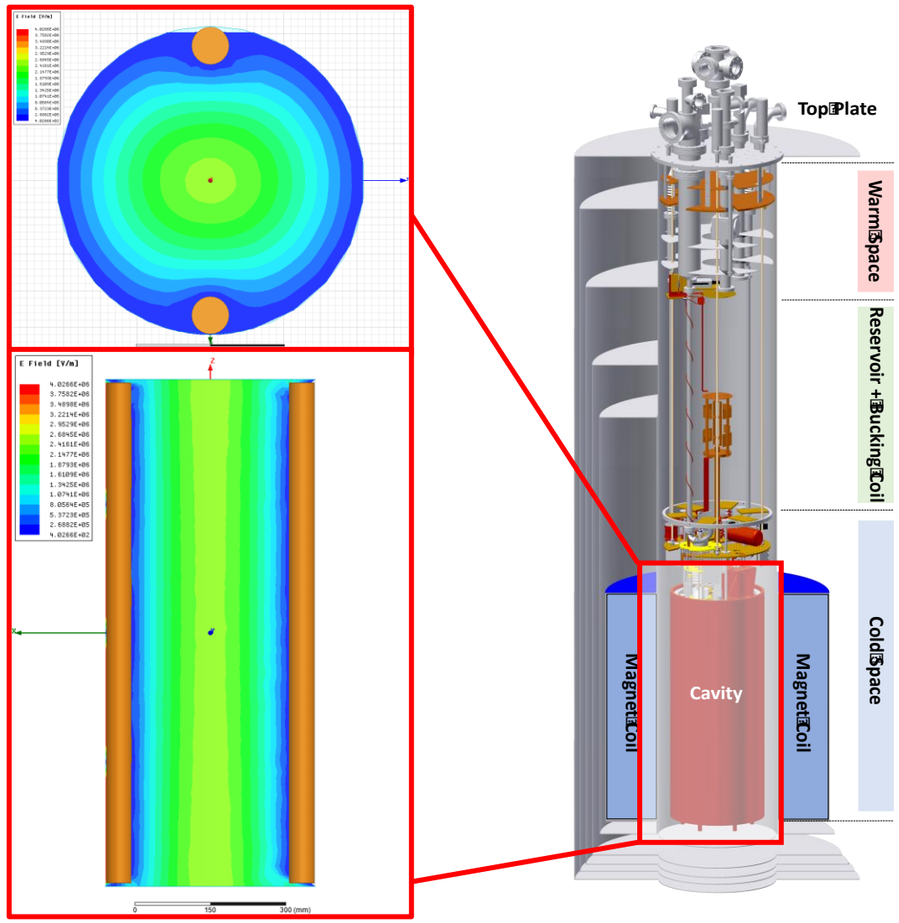


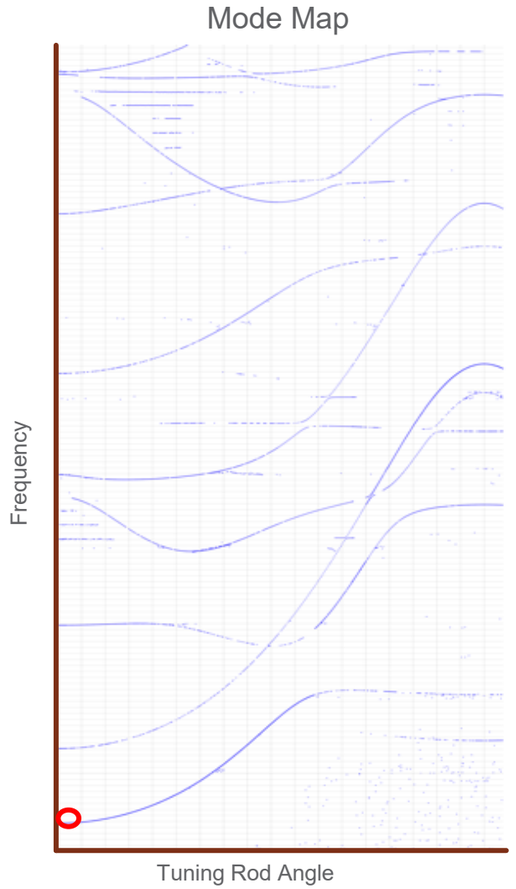
$$f = \frac{c^2}{h} m_a$$

Scanning experiment

1. Calibrate to frequency
2. Look for axion signal
3. Move rod to next frequency

Scanning Frequencies with Tuning Rod



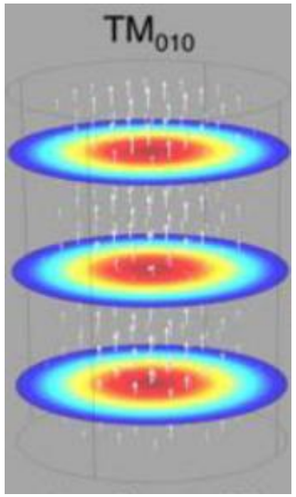


Axion photon power in a haloscope

$$P_{axion} = 2.2 \cdot 10^{-23} W \cdot \{(\frac{g_\gamma}{0.36})^2 \cdot \frac{\rho_0}{0.45\ GeV\ cm^{-3}} \cdot \frac{f}{740\ MHz}\} \cdot \{\frac{V}{136\ L} \cdot \left(\frac{B_0}{7.6\ T}\right)^2 \cdot \frac{Q_L}{30000} \cdot \frac{C_{lmn}}{0.4}\}$$

$$C_{lmn} = \frac{\left(\int \vec{E}_{lmn}(\vec{x}, t) \cdot \vec{B}_{ext}(\vec{x})\, dV\right)^2}{\int \vec{B}_{ext}{}^2 dV \int \epsilon_r \vec{E}_{lmn}^2 dV}$$

$$SNR = \frac{P_{axion}}{kT_{sys}} \sqrt{\frac{t}{\Delta f}}$$



Model- Dependent Parameters

- g_γ – Coupling Constant
- f – Axion frequency
- ρ_0 – Dark matter halo density

Experimental Parameters

- B_0 – External magnetic Field
- V – Cavity volume
- Q_L – Cavity quality factor
- C_{lmn} – Cavity form factor
- SNR – Signal to Noise Ratio
- T_{sys} – System noise temperature
- t – Integration time of FFT
- Δf – Bandwidth of FFT

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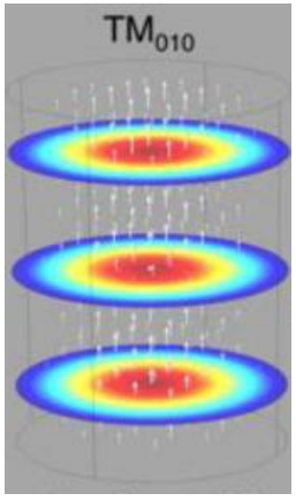
Exclusion limits
Set in $g_{a\gamma\gamma}$ assuming a value of ρ_a.

Nominal: $\rho_a = \rho_{DM}$
Sub-nominal: $\rho_a < \rho_{DM}$

$$C_{lmn} = \frac{\left(\int \vec{E}_{lmn}(\vec{x}, t) \cdot \vec{B}_{ext}(\vec{x})\, dV\right)^2}{\int \vec{B}_{ext}^{\,2} dV \int \epsilon_r \vec{E}_{lmn}^2 dV}$$

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Axion Scanning Rate

$$\frac{df}{dt} \approx 1.98 \frac{GHz}{year} \left(\frac{g_\gamma}{0.36}\right)^4 \left(\frac{f}{1\ GHz}\right) \left(\frac{\rho_a}{0.45 \frac{GeV}{cc}}\right)^2 \cdot \left(\frac{5}{SNR}\right)^2 \left(\frac{B_0}{7.6T}\right)^4 \left(\frac{V}{136l}\right)^2 \left(\frac{Q_L}{30{,}000}\right) \left(\frac{C_{lmn}}{0.4}\right)^2 \left(\frac{0.35K}{T_{sys}}\right)^2 *$$

Combining signal power with SNR we can arrive at **the instantaneous scan rate** for a haloscope

*Does not include deadtime (Calibration, Candidate rescans, engineering studies, etc.)

Model- Dependent Parameters
- g_γ – Coupling Constant
- f – Axion frequency
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Experimental Parameters
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The Axion Dark Matter eXperiment (ADMX)

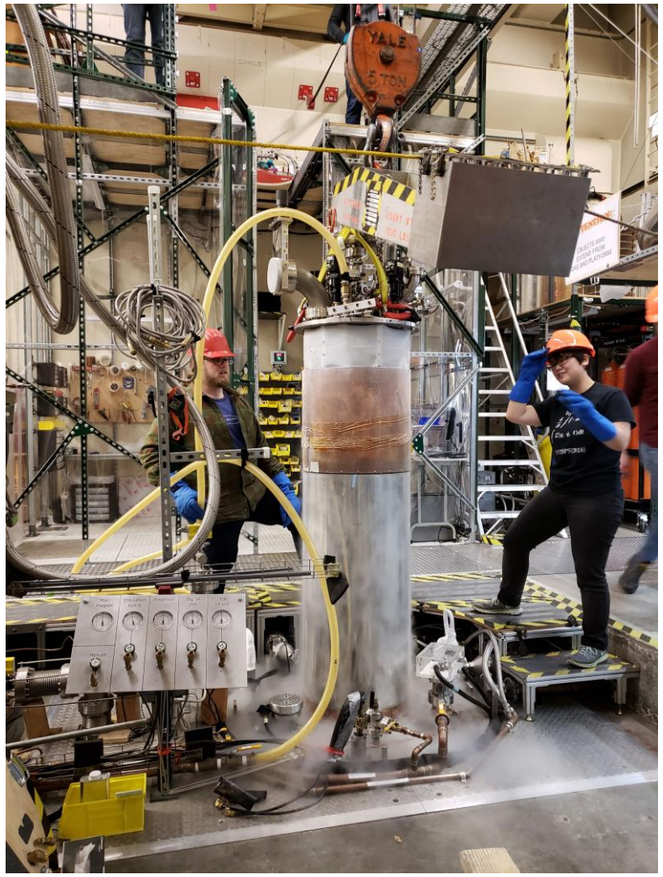
- One of the first ‘discovery’-sensitive axion haloscopes
- Started in 1995 at Lawrence Livermore National Laboratory (LLNL)
- Sited at University of Washington CENPA in Seattle since 2010
- First to exclude DFSZ axions in 2018
- On-going upgrades enable us to scan more frequencies
- Currently operating our 4th science run! (Run 1D)



ADMX CENPA Site. Photo: Mark Stone



ADMX Insert in Clean Room during upgrades.
Photo Credit: Scientific American



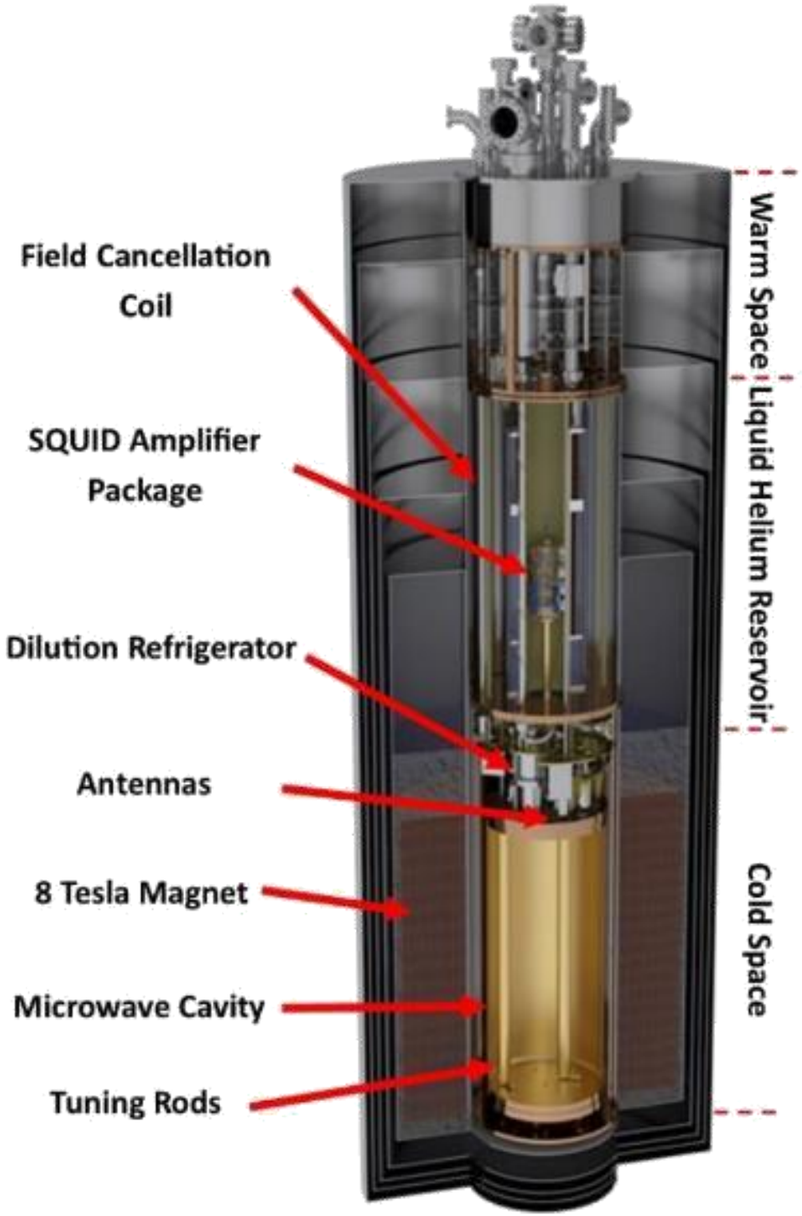
Insert extraction at end of science run (2018).

ADMX Insert

- ADMX insert has many systems to optimize scan rate

Parameter	Equipment
Maximize B^2V	8T magnet with 0.5 M bore
Minimize Thermal Noise	Helium Dilution Refrigerator
Max low-noise amplification	Quantum Amplifiers
Maximize resonator Q in field	Copper cavity resonator
Maximize frequency range	Tuning rod system

- These systems are then supported by more systems
  - ‘Bucking’ field-cancellation Coil
  - More RF electronics
  - Helium Liquefaction plant
  - Great Science Operators!



Operations Cadence

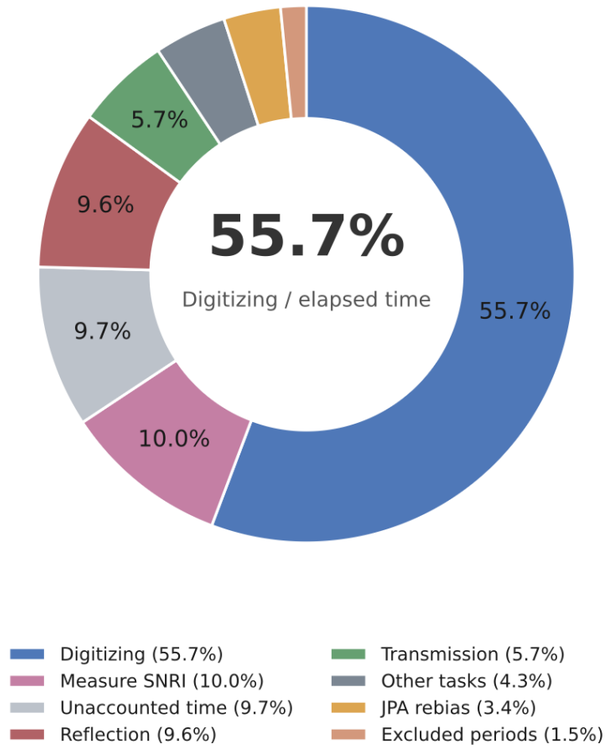
Data-taking Loop:

1. The cavity is characterized by Network Analyzer (VNA) reflection and transmission measurements (f_0, Q_L, β)
2. The receiver gain and noise is measured and possibly re-biased for the given f_0
3. 100 second power digitization is taken (Axion data)
4. Tuning rod is stepped to the next f_0 accordingly

run1d_part2 - nibble0

Time periods (Pacific time): December 23, 2025 - January 20, 2026; May 30, 2026 - August 19, 2026
Frequency range: 1,250.0 - 1,270.0 MHz

Elapsed time: 109.0 days | Digitizing fraction: 55.7%

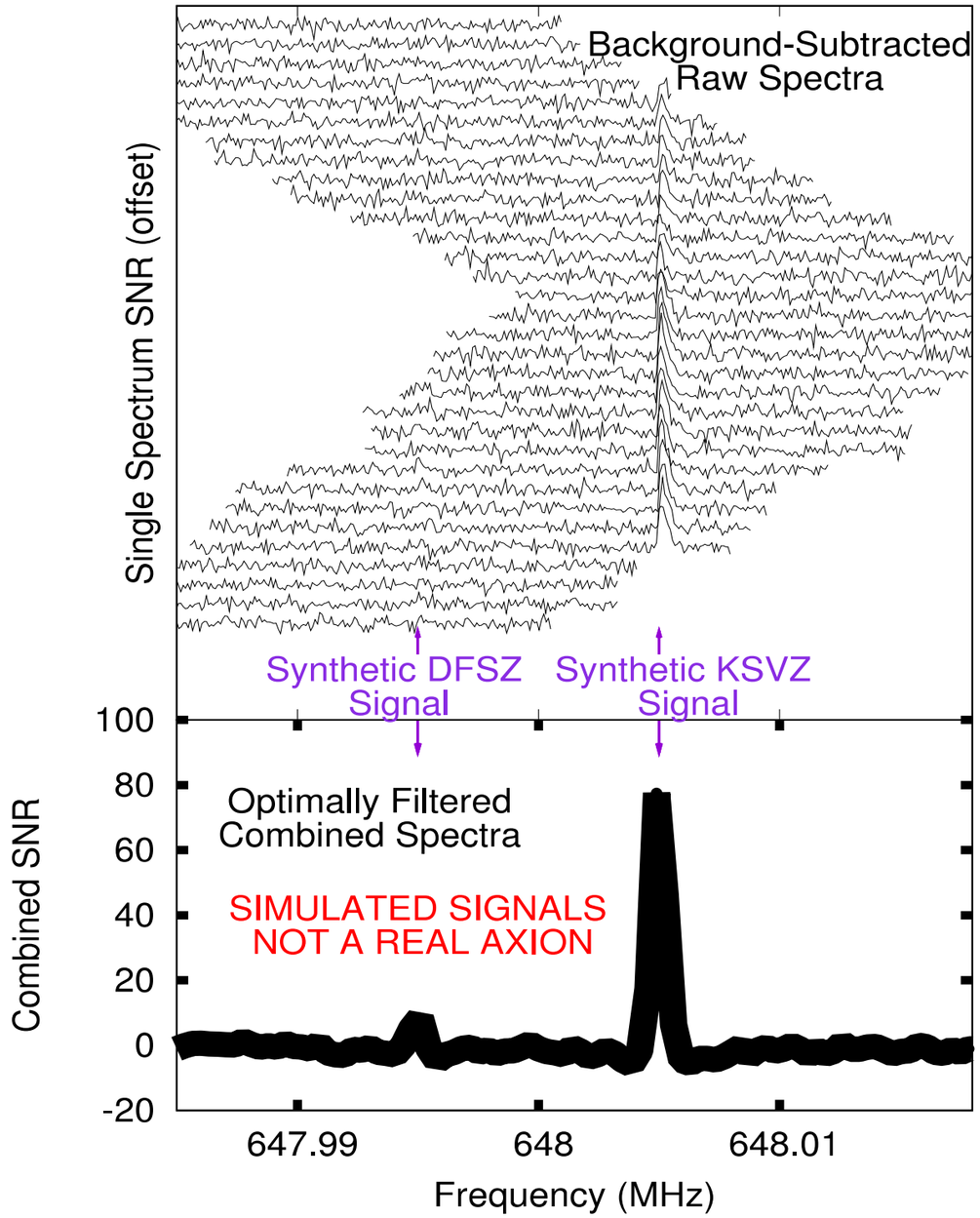


Category	Duration	% elapsed	Records
Digitizing	60.8 d	55.7%	49766
Measure SNRI	10.9 d	10.0%	52357
Unaccounted time	10.6 d	9.7%	-
Reflection	10.4 d	9.6%	132865
Transmission	6.2 d	5.7%	75305
JPA rebias	3.7 d	3.4%	3102
Monitor JPA	2.2 d	2.1%	48679
Excluded periods	1.7 d	1.5%	-
Transmission gain	22.7 h	0.9%	11694
Widescan	12.8 h	0.5%	6054
Wide reflection	12.3 h	0.5%	6043
Reflection (JPA off)	4.6 h	0.2%	6385
Move rods	3.9 h	0.1%	32556
Check for fill	2.4 h	0.1%	42026
Recalculate rod speed	49.4 min	0.0%	29130
Reload digitizer driver	26.6 min	0.0%	26
Wide power	7.6 min	0.0%	2

DAQ paused outside excluded periods: 6.0 d
Pause-state coverage: complete
Paused time can overlap tasks; it is not an extra slice.

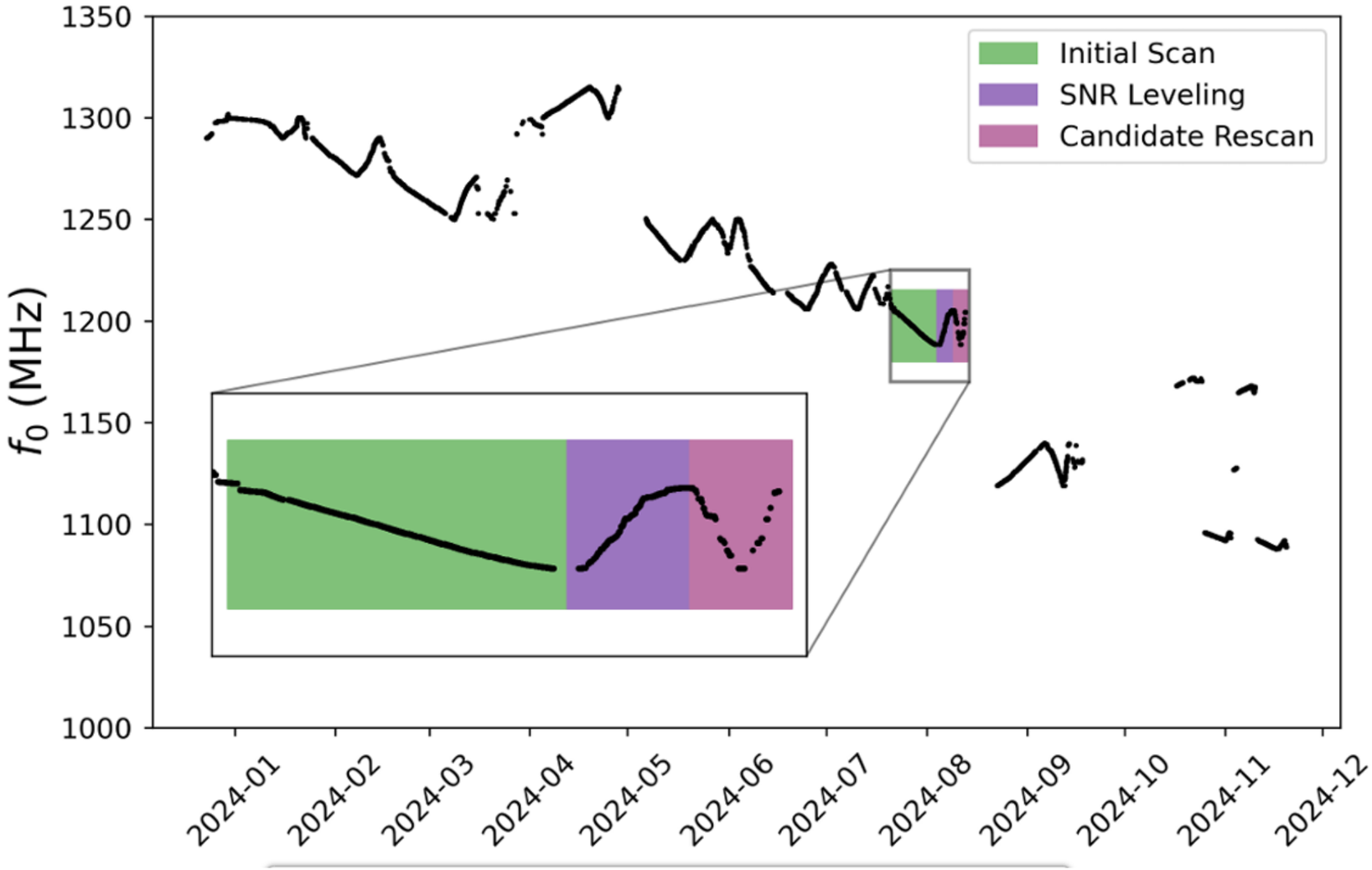
Search Procedure

1. Each $100\ s$ time-series is split into 10^4 $100\ \mathrm{ms}$ segments and FFT performed
2. Spectra are normalized by fits and associated with run parameters
3. Prepared spectra are co-added together in weighted sum based on run parameters making a grand spectrum
4. Power excesses $> 3\sigma$ are axion candidates and are subject to additional scans/tests
5. Once all candidates are eliminated, an exclusion limit is set.

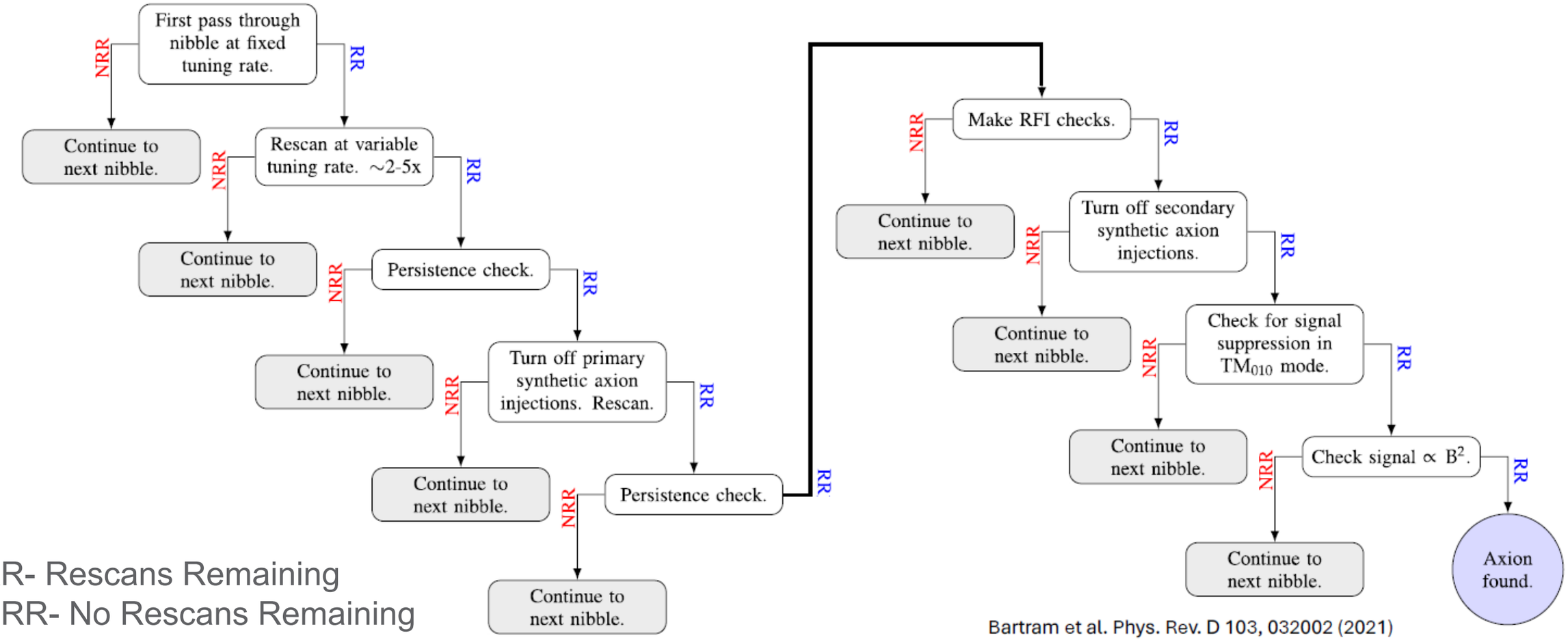


Run Overview

- Data runs are broken up into ‘nibbles’ of frequency space
- Nibbles are initially scanned slow at fixed rate
- SNR leveling fills in areas of lower sensitivity
- Remaining candidates are rescanned individually



Data Taking Decision Tree

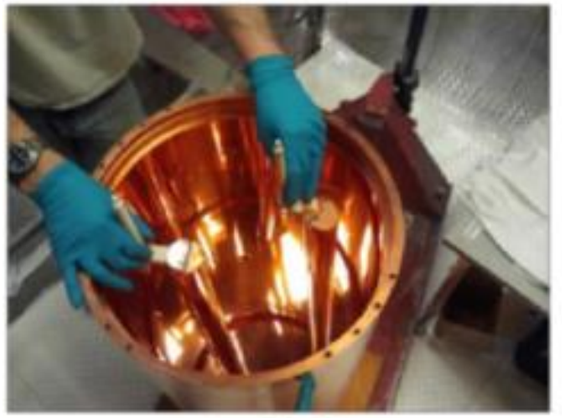


RR- Rescans Remaining
NRR- No Rescans Remaining

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

Previous ADMX Limits

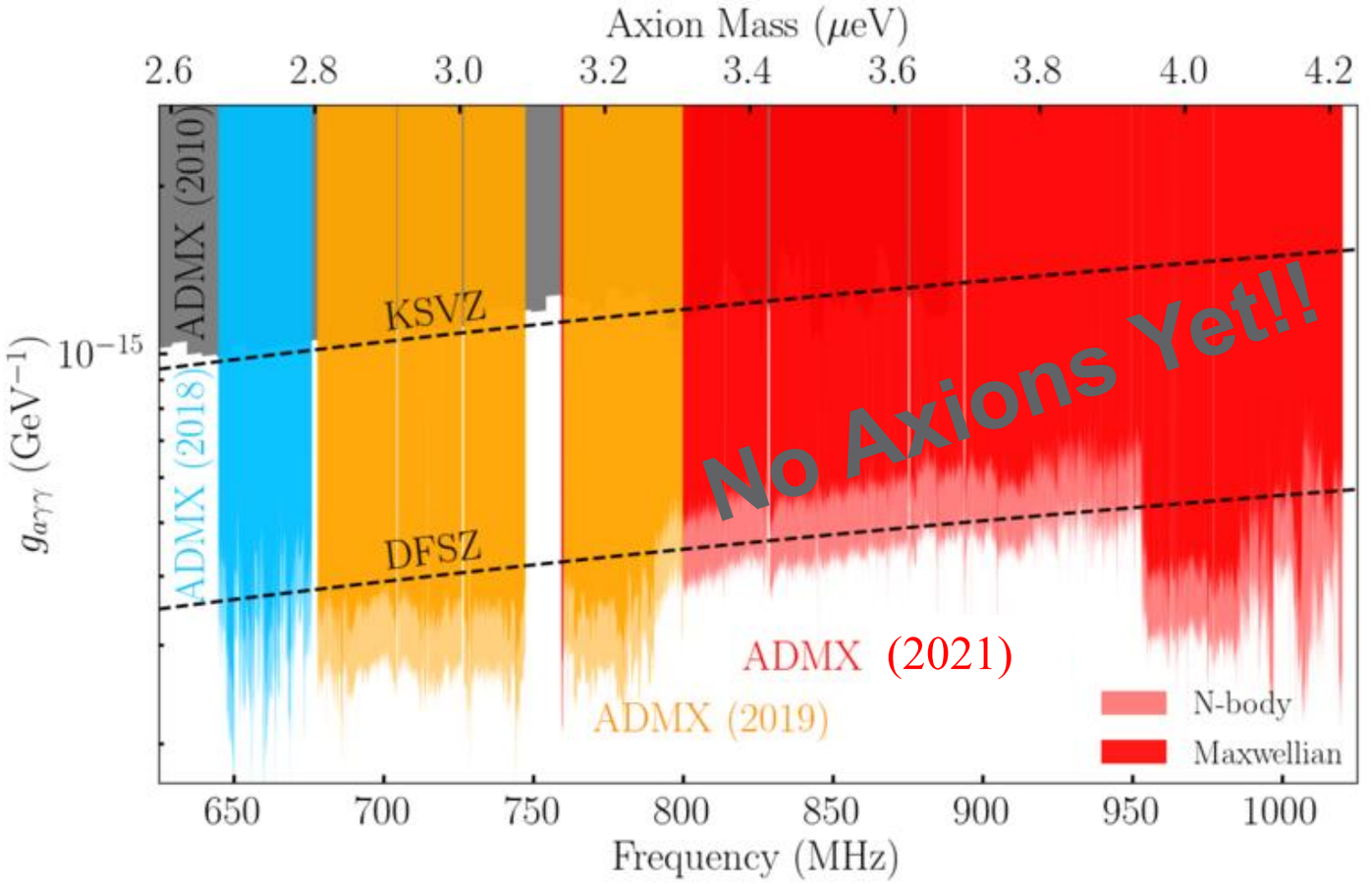
- Increasing tuning rod size shifts frequency range upward
- Gaps are due to mode crossings
- Exclusion set by two different axion thermal models



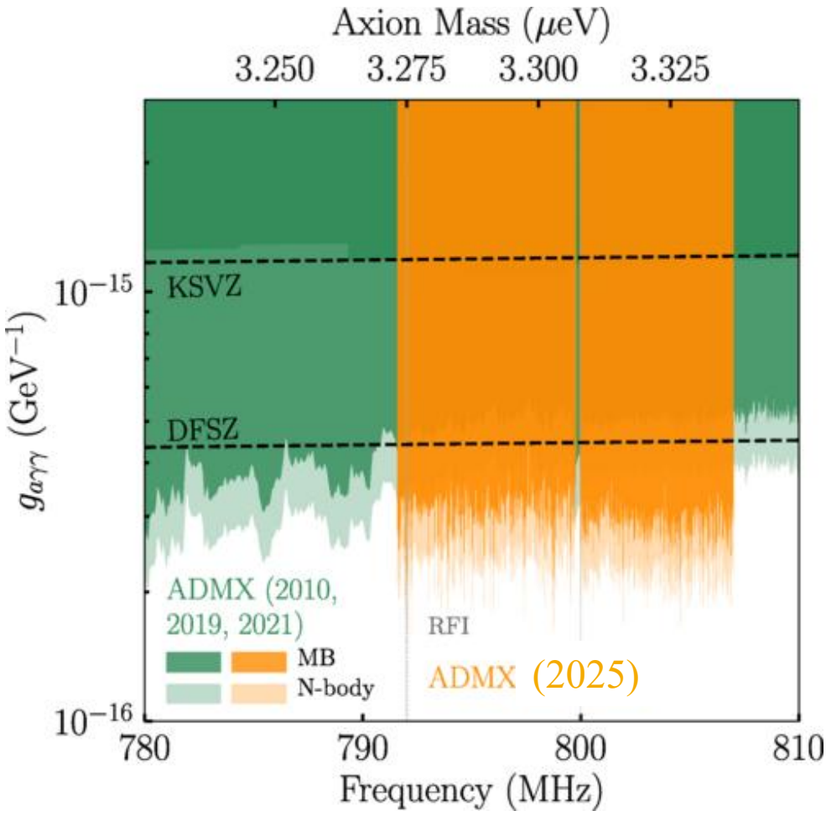
Run 1A+1B
640-800 MHz



Run 1C
800-1020 MHz



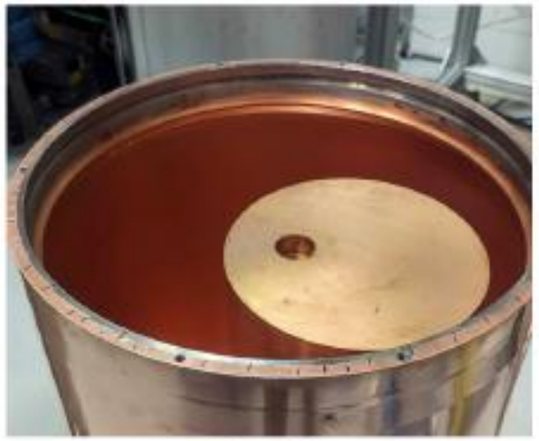
(2021) https://doi.org/10.1063/5.0122296



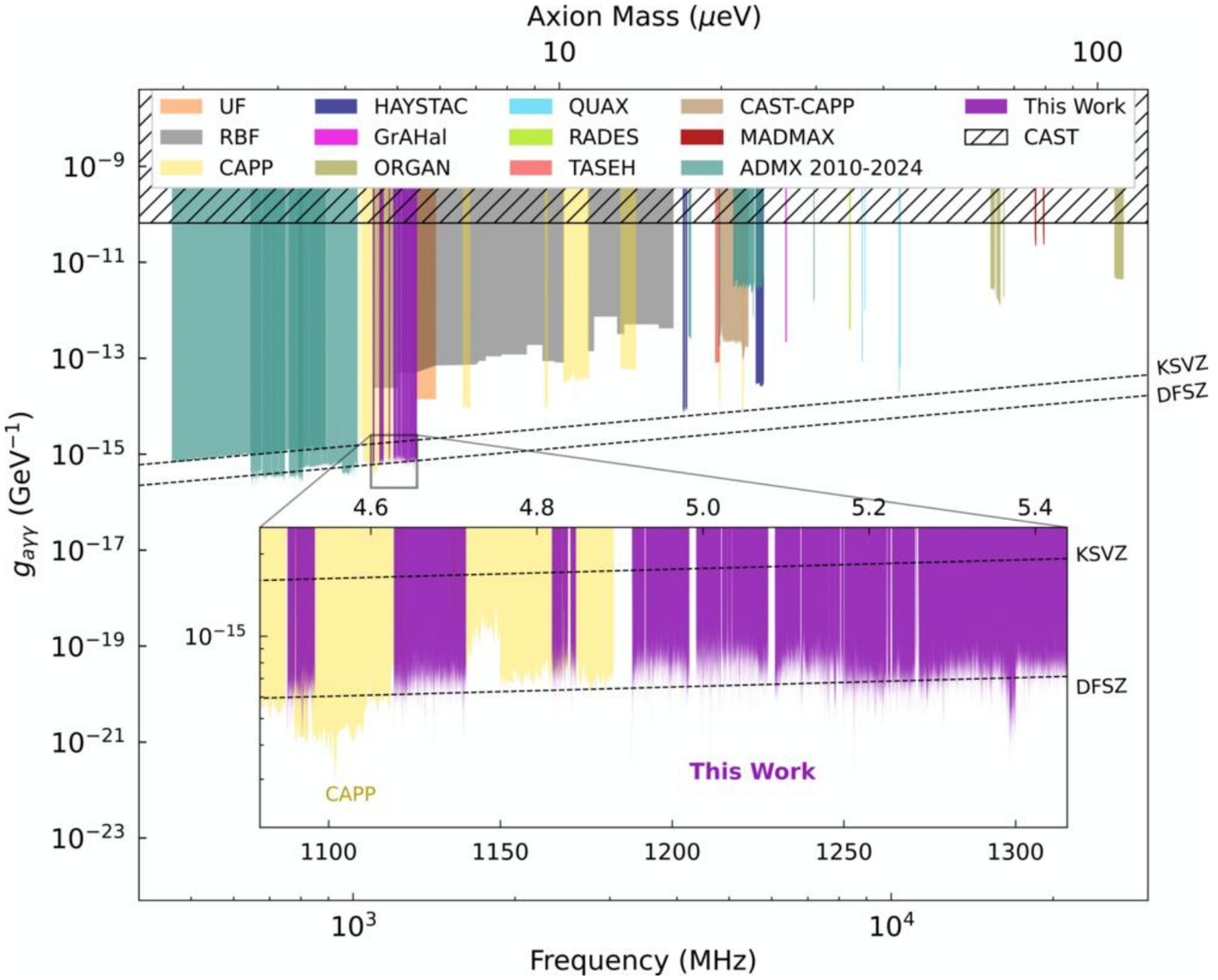
(2025) https://doi.org/10.1103/PhysRevLett.134.111002

Most Recent Published Limits

- Currently using maximum sized tuning rod to maintain DFSZ sensitivity for a single cavity
- Aimed at reaching KSVZ at sub-nominal DM Density, and nominal DFSZ limits



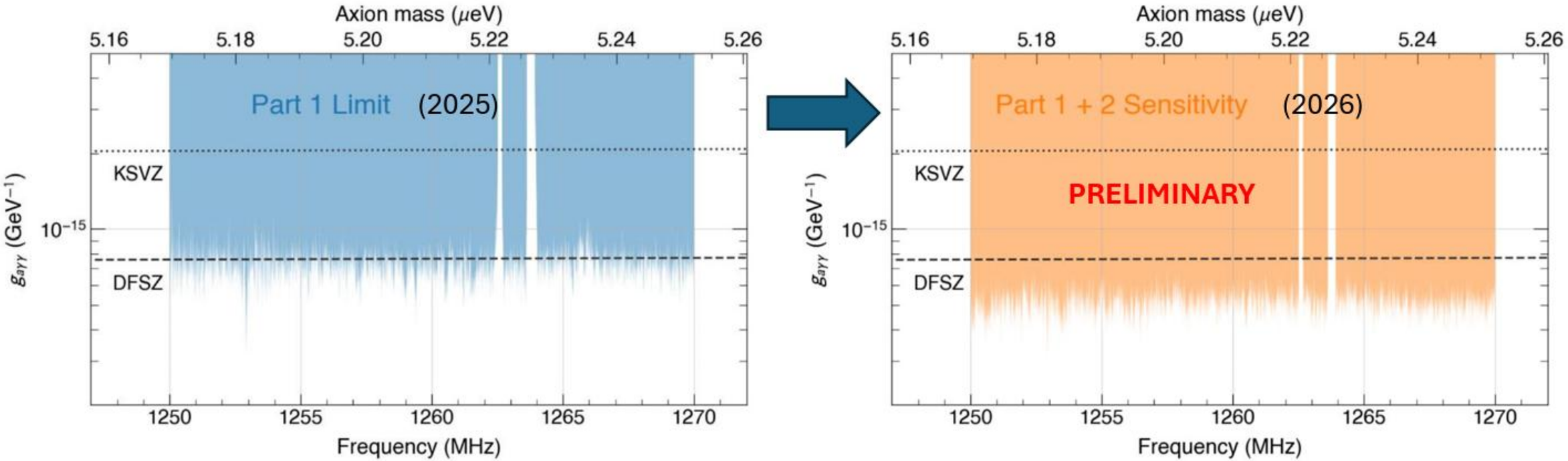
Run 1D
1020-1390 MHz



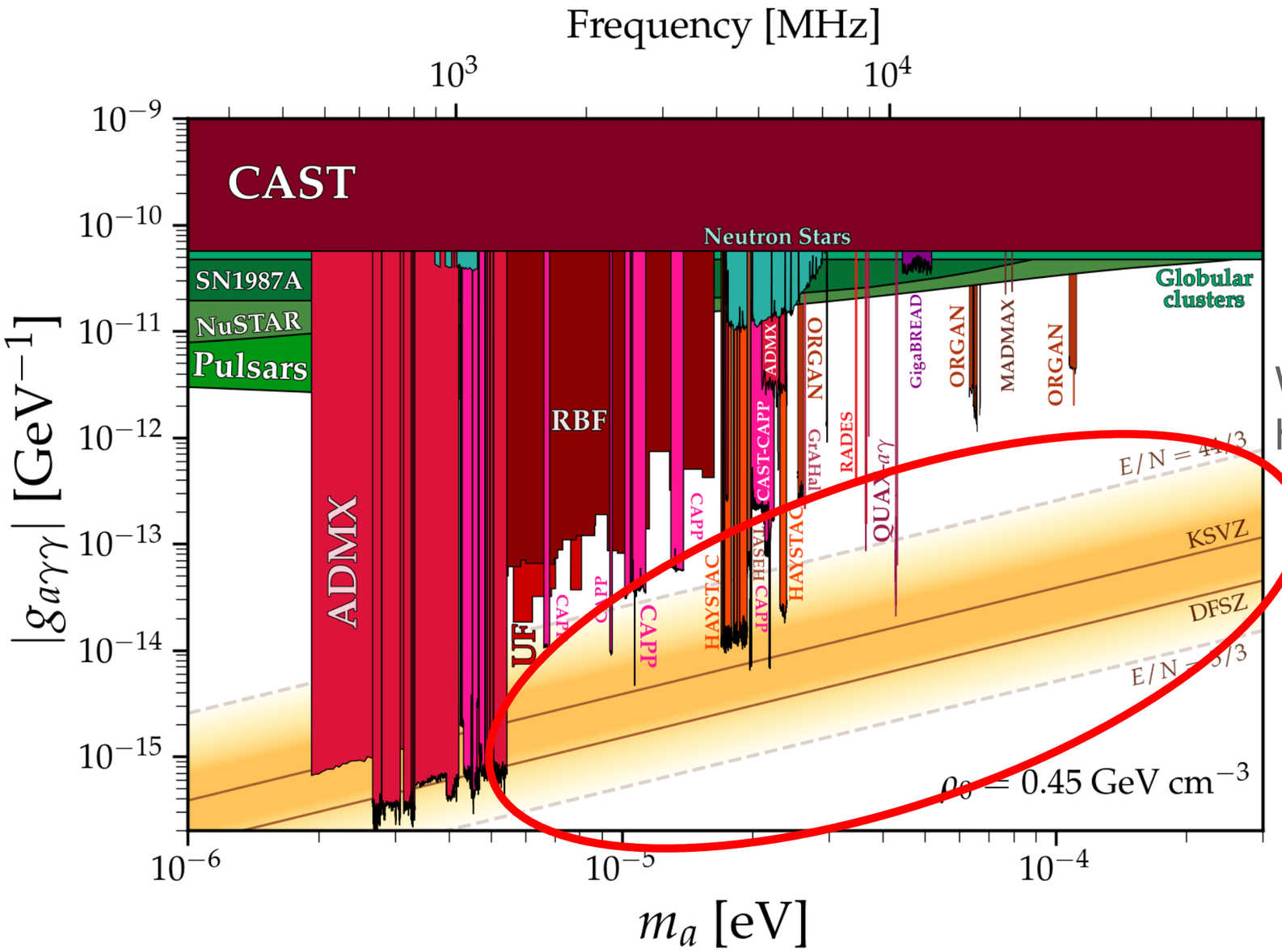
(2025) https://doi.org/10.1103/d7mg-6sqq

2026 Run Status

- Extend Sensitivity beyond DFSZ limit to sub-nominal Dark Matter density
- Accomplish this with better amplifier performance
- 1-1.3 GHz



Where are we headed?



We want to look here next!

Challenges at higher frequencies!

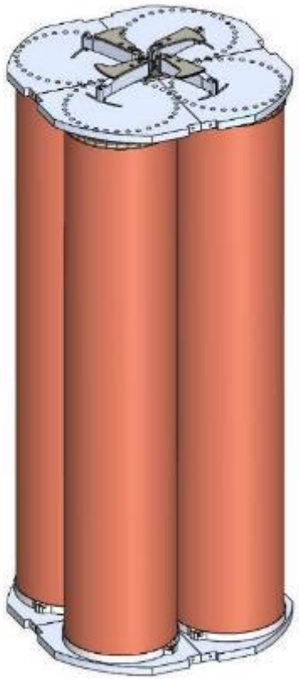
Haloscope frequency scan rate:

$$\frac{df}{dt} \approx 1.98 \frac{GHz}{year} \left(\frac{g_\gamma}{0.36}\right)^4 \left(\frac{f}{1\,GHz}\right) \left(\frac{\rho_0}{0.45\frac{GeV}{cc}}\right)^2 \cdot \left(\frac{5}{SNR}\right)^2 \left(\frac{B_0}{7.6T}\right)^4 \left(\frac{V}{136l}\right)^2 \left(\frac{Q_L}{30{,}000}\right) \left(\frac{C_{lmn}}{0.4}\right)^2 \left(\frac{0.35K}{T_{sys}}\right)^2 *$$

$V \propto f^{-2}$

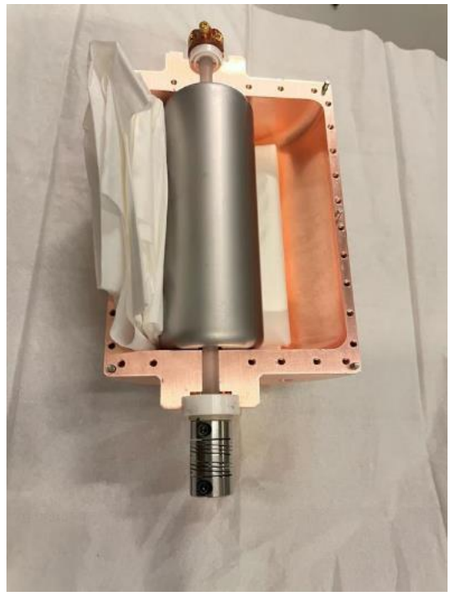
$Q \propto f^{-2/3}$

$T_{sys} \propto f$





ADMX Run 2 uses a 4-cavity array to maintain volume (1.3-2 GHz)

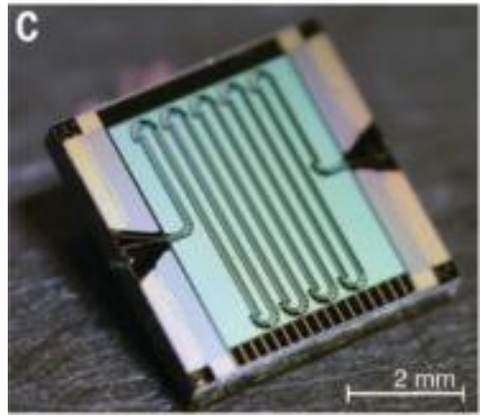


ADMX-Sidecar Nb_3Sn Superconducting Tuning Rod

arXiv:2408.03444

$$\frac{df}{dt} \propto f^{-14/3}!!!!$$

Need innovation to scan fast enough!



Novel TWPAs, Quantum Squeezing, Qubit Photon Counting circumvent noise limits

ADMX Near Future

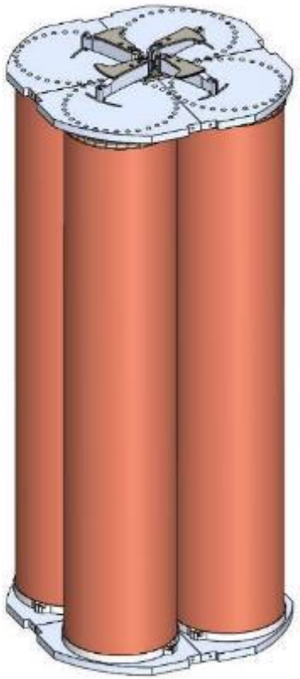
- Run 2 uses 4-cavity array to maintain volume
- Total Volume: 85 L (62.5% of current)
- Compatible with existing magnet and cryostat
- Minimal site renovation
- 1.3-2.2 GHz cavity coverage (Two rod sizes)
- 4 separate RF readouts
- Digital Cavity Power Combining

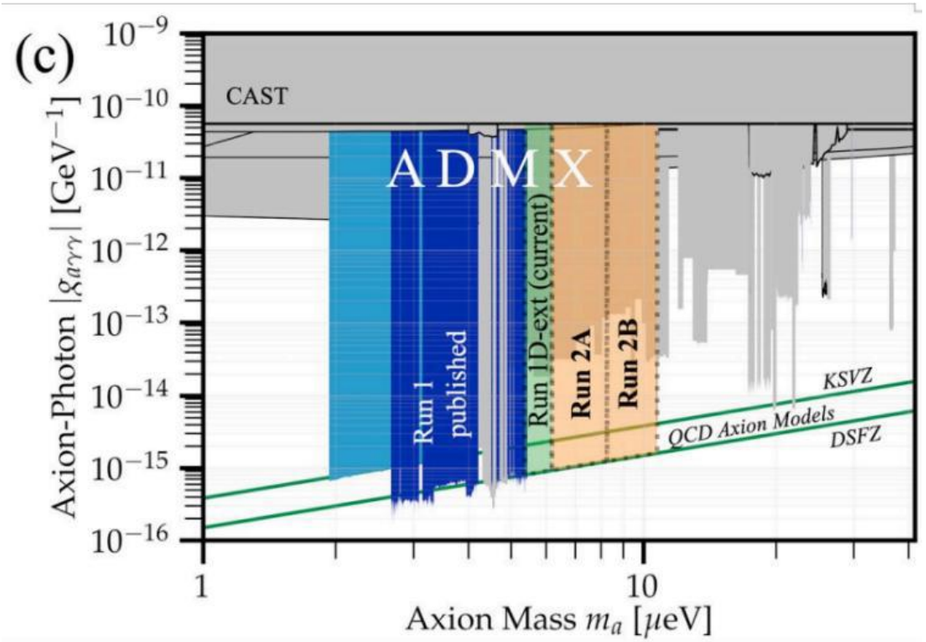


Cavity Array Testing at LLNL and Fermilab



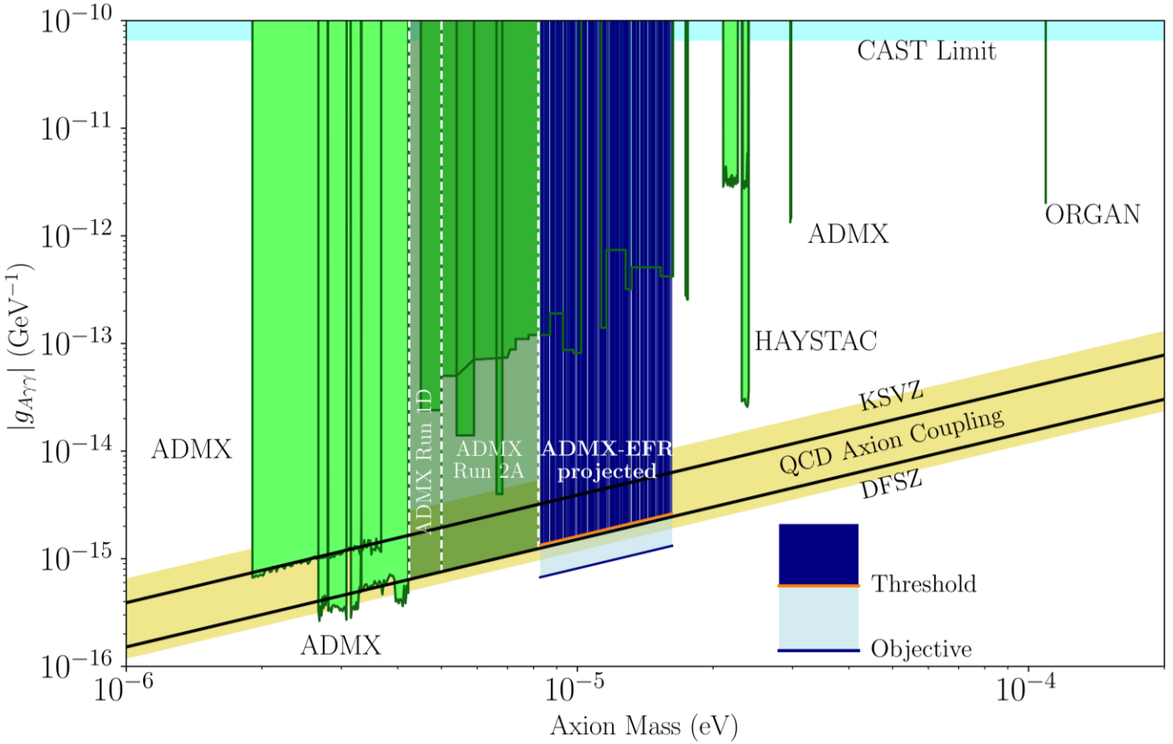
RFSoC (ZCU208) RF transceiver development at PNNL

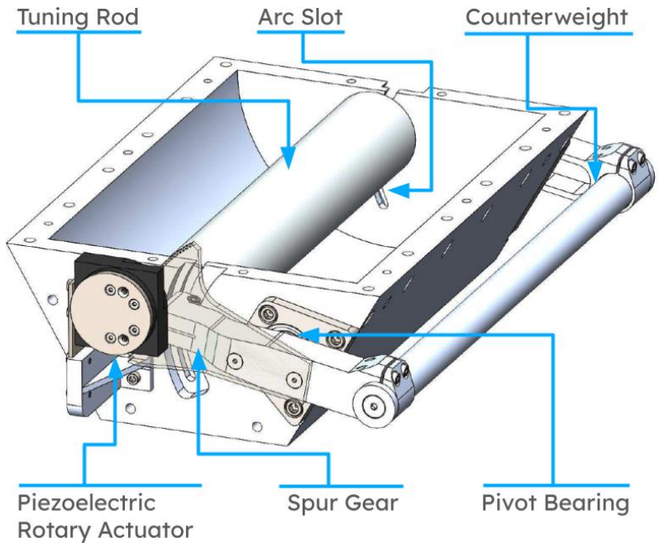


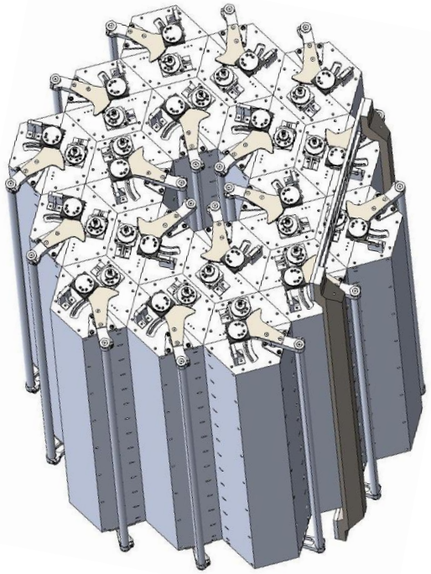


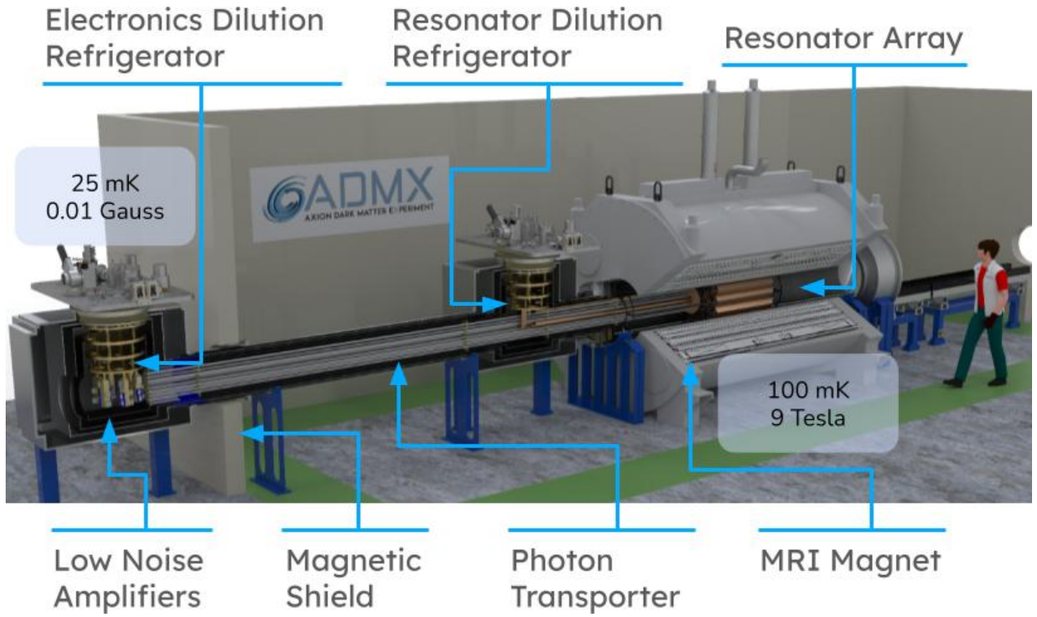
ADMX Further Future

- ADMX Extended Frequency Range (EFR)
- 18-Cavity Array covering 2-4 GHz
- Uses 9.4T, 0.8 by 3.1 m, MRI Magnet
- Paper outlining conceptual design and sensitivity on arXiv very soon







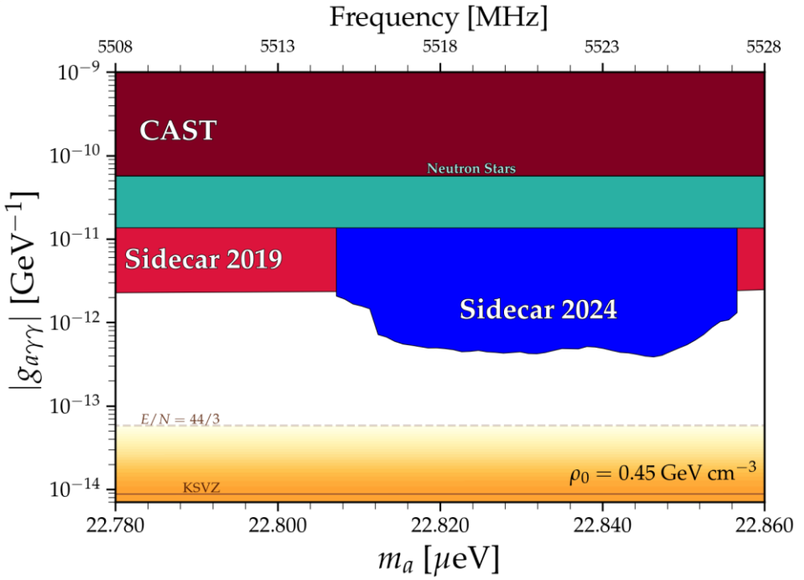


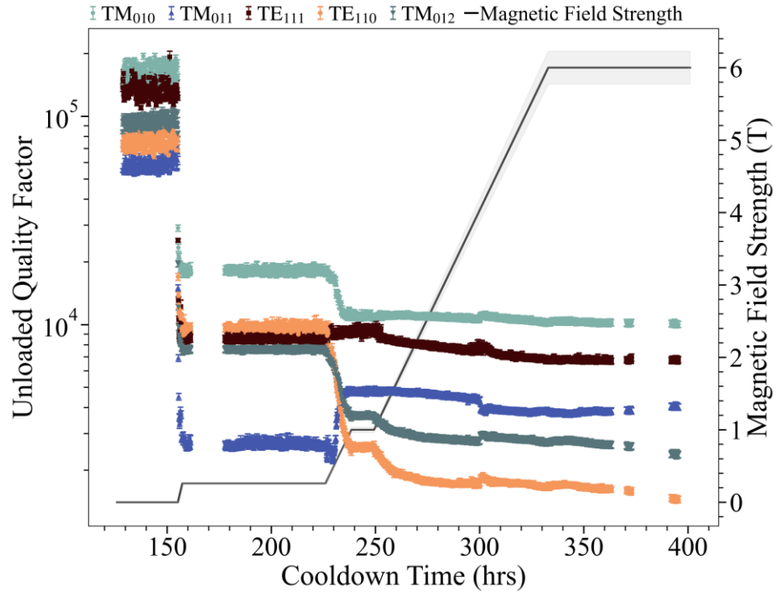
Further R&D: Superconducting Cavities

- Anomalous skin depth of copper: $Q \propto f^{-2/3}$
- **SRF** might circumvent this
- Requires overcoming fluxon dissipation in magnetic field
- Hybrid material construction may minimize loss

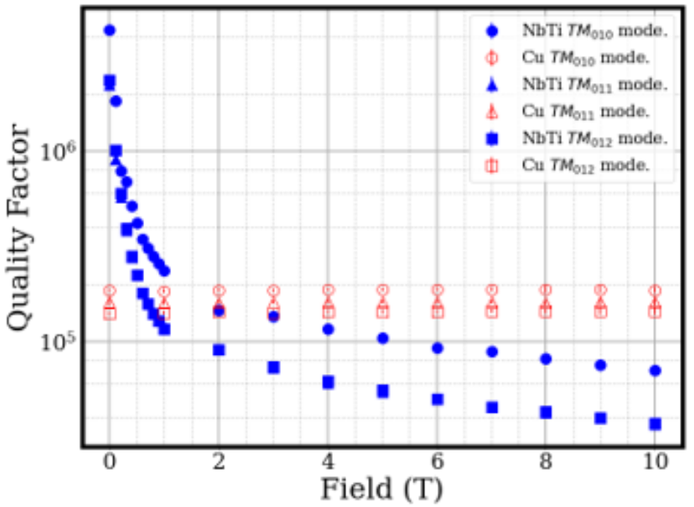


Nb3Sn Tuning Rod Sidecar (2024): arxiv 2408.03444





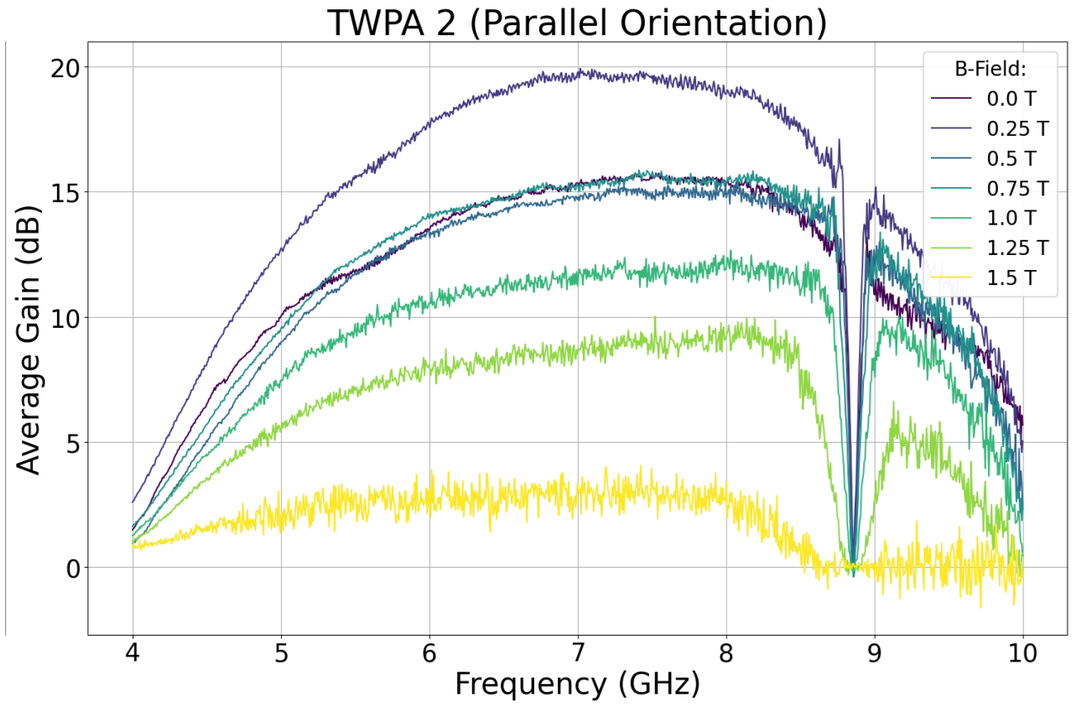
Characterization of Al-Nb3Sn cavity (2026): arXiv:2611.00087

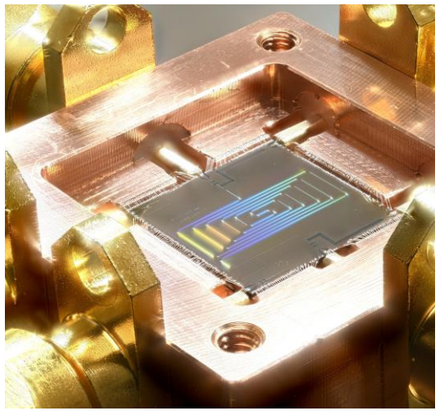


NbTi Cavity Multi-Mode Analysis (2023): doi.org/10.1063/5.0122296

Further R&D: Field Resistant Quantum Amplifiers

- Space becomes more limited for other components in Multi-cavity searches
  - Example: Current field-free regions have limited space for sensitive electronics
  - Field Resistant Amplifiers remove this constraint
- PNNL testing of NbTiN Kinetic Inductance Travelling-Wave Parametric Amplifiers (KTWPAs) from National Institute of Standards and Technology (NIST)
  - Positive gain up to 1.5T!!

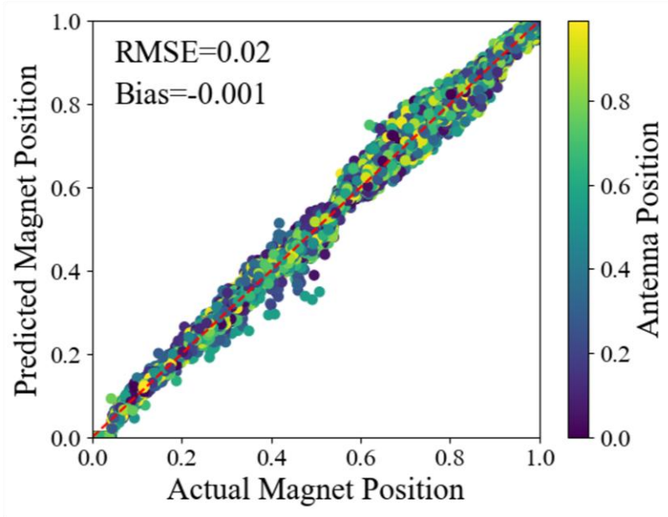




ADMX SIDETRAC Field Resistant KITWPA

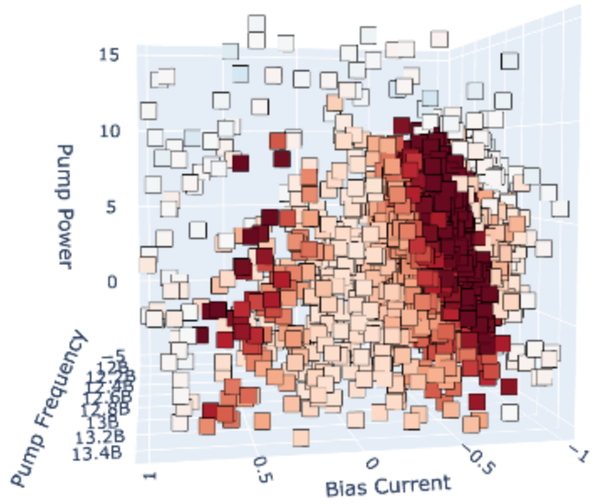
Further R&D: AI Monitoring and Control

- Multi-cavity systems become increasingly complex
- Operational monitoring untenable
- Coherent cavity combining introduces new sources of dead time
- Space is limited for more diagnostic equipment (thermometers, hall probes, etc)



RF circulator S-parameters as a magnetic field and Temperature sensor!



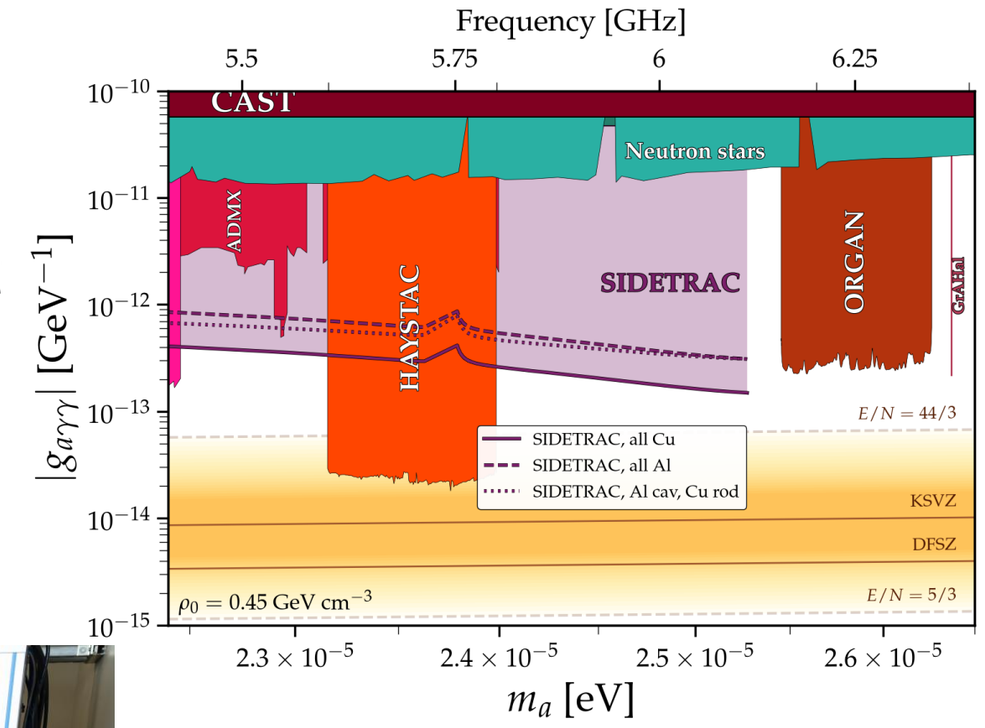


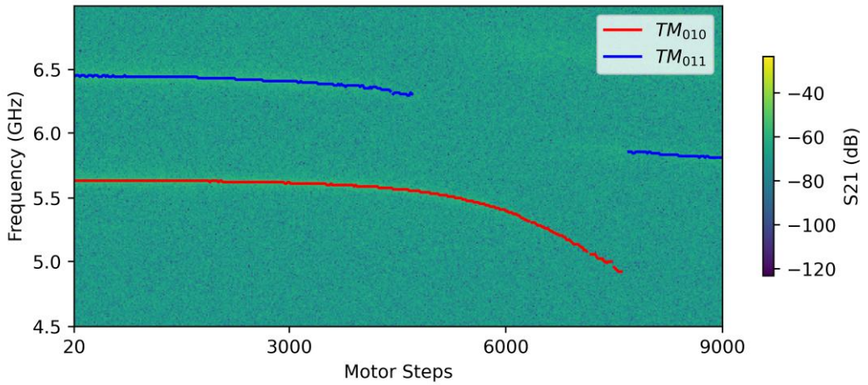
Reinforcement Learning for Auto-tuning amplifiers!

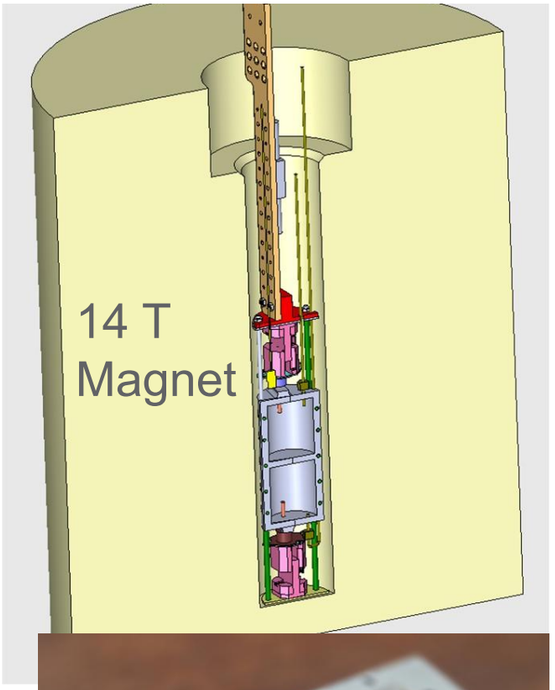
Rev. Sci. Instrum. 96, 123102 (2025)

PNNL Work: ADMX-SIDETRAC

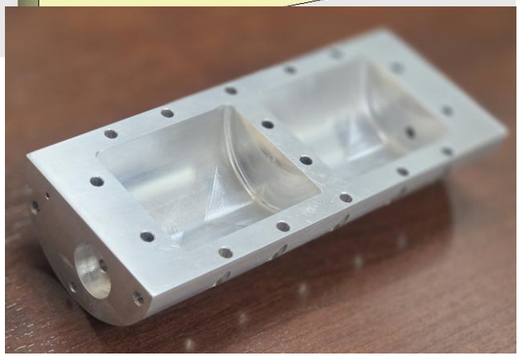
- R&D 2-Cavity Axion search at PNNL!
- PI: Christian Boutan
- $R_{cav} \cong 18.8\text{mm}$

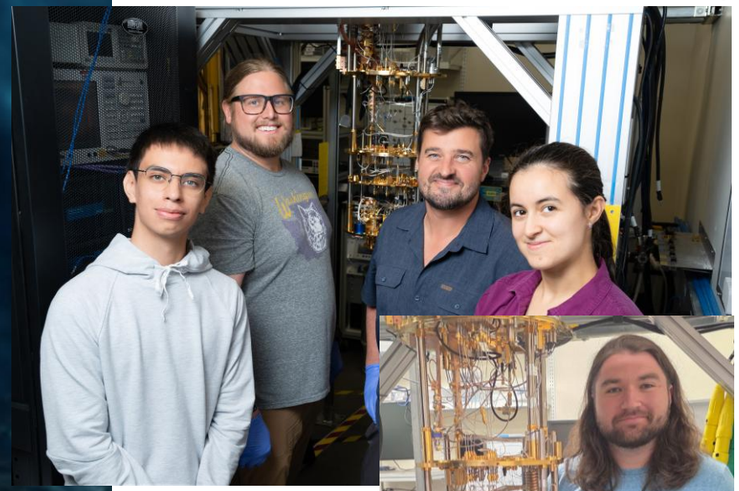




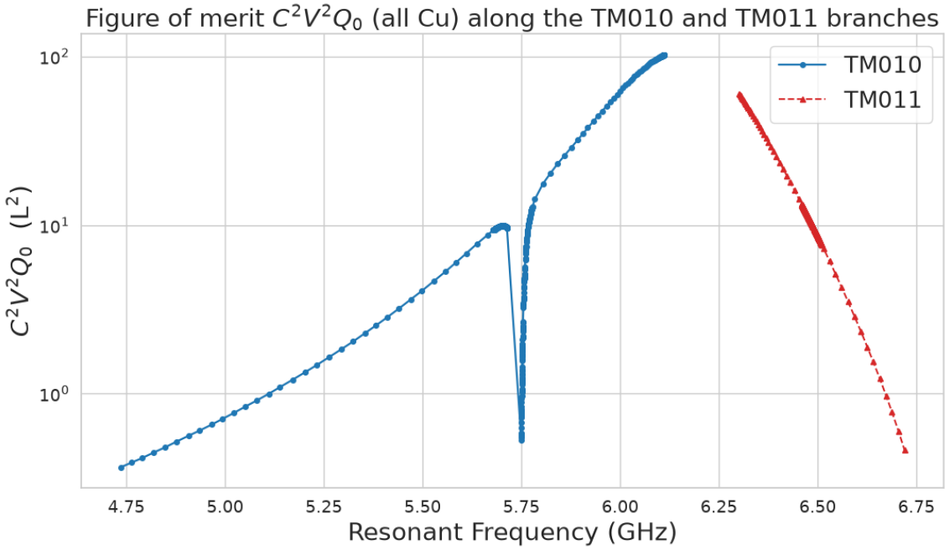






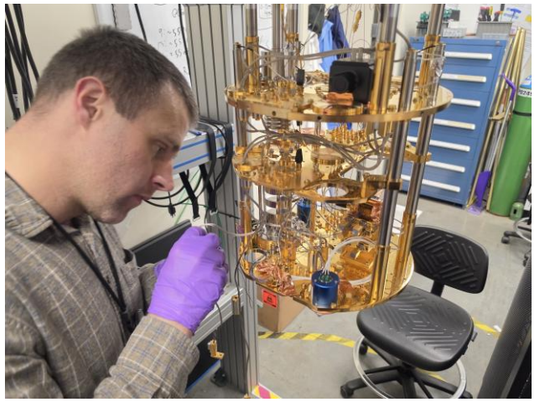


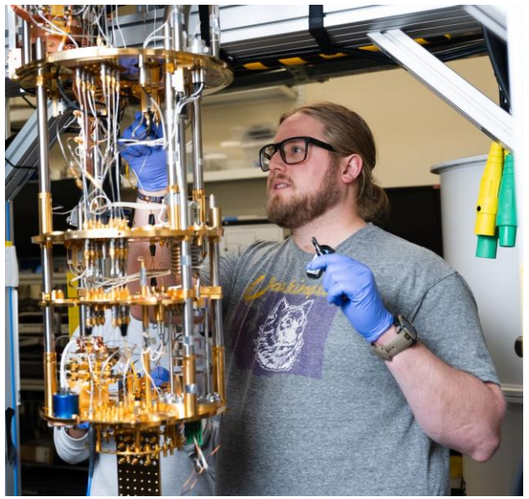
SIDETRAC Team

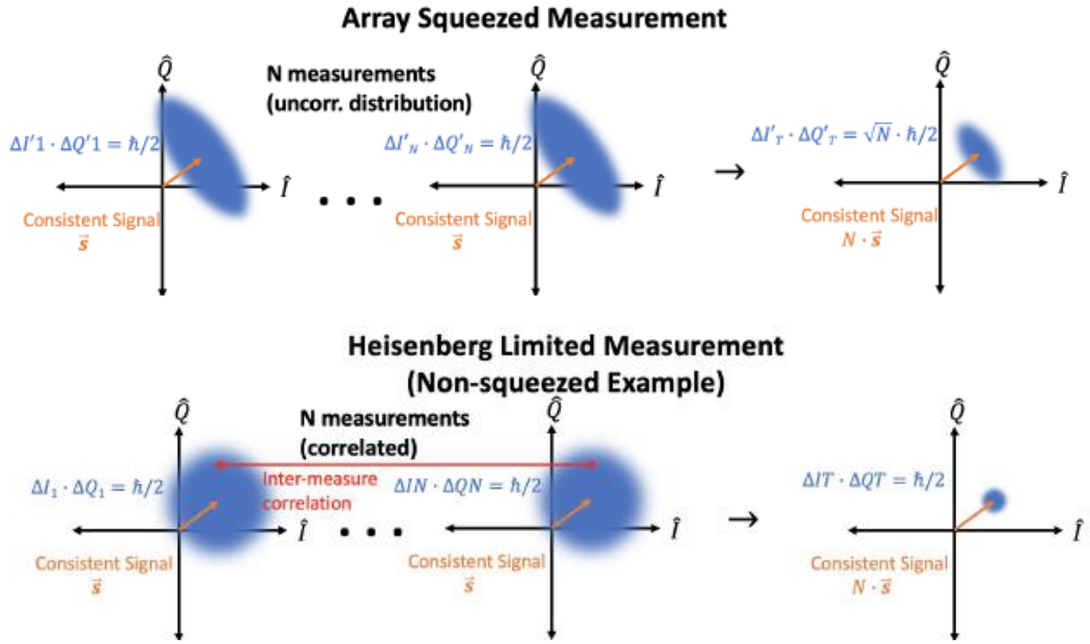


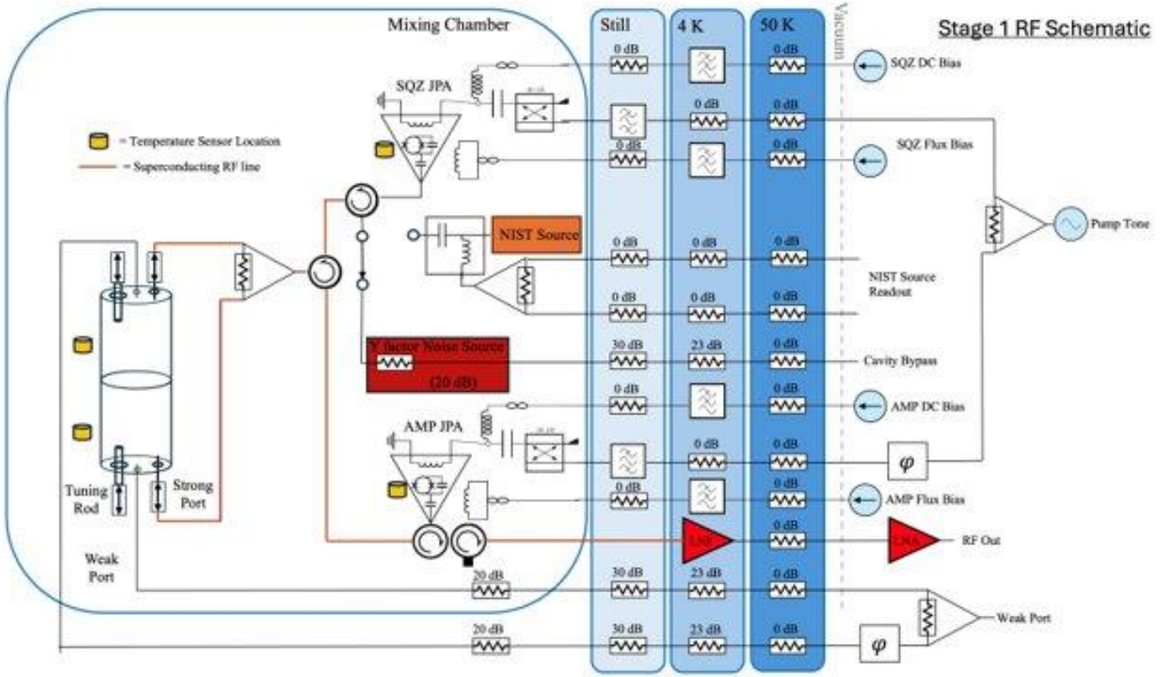
PNNL work: VEBAX

- Very Entangle Bose Array eXperiment
- PI: Erik Lentz
- **Heisenberg-Limited** haloscope at PNNL
- Stage 1 uses SIDETRAC cavity system
- Coherent, analog cavity power combining
- Quantum-Squeezing of JPA amplifiers









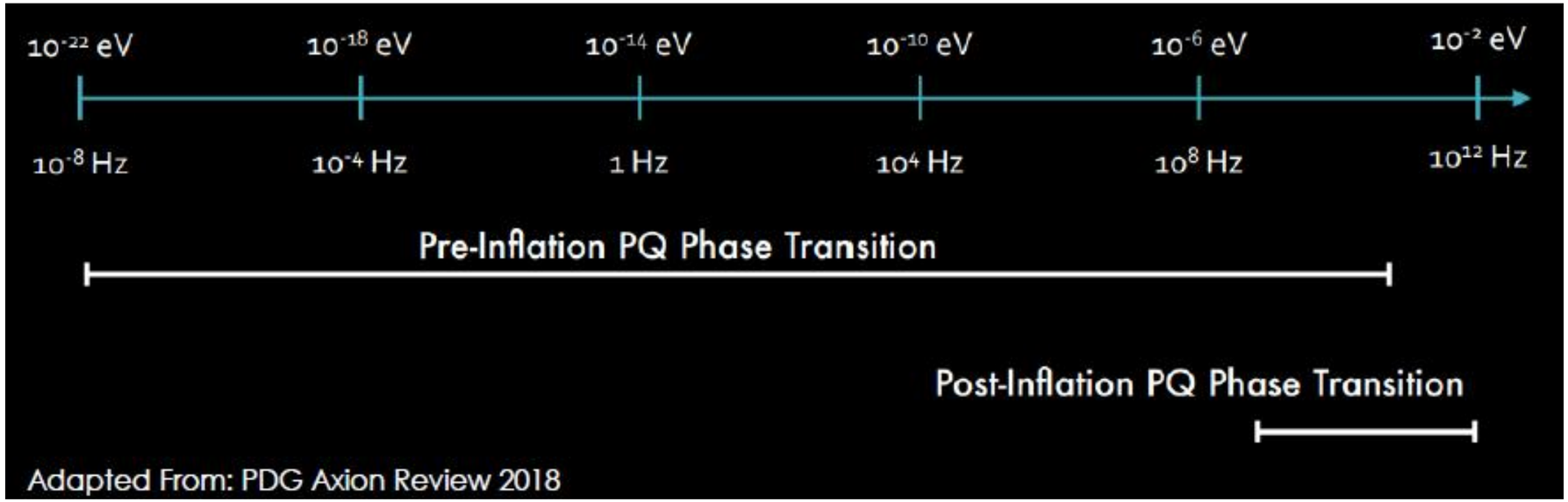
Thank you!



This work is supported by U.S. Department of Energy through Awards No DE-SC0009800, No. DE-SC0009723, No. DE-SC0010296, No. DE-SC0010280, No. DE-SC0011665, No. DEFG02-97ER41029, No. DE-FG02-96ER40956, No. DE-AC52-07NA27344, No. DE-C03-76SF00098, No. DE-SC-0022148 and No. DE-SC0017987. Fermilab is a U.S. Department of Energy, Office of Science, HEP User Facility managed by Fermi Research Alliance, LLC (FRA), under Contract No. DE-AC02-07CH11359. Additional support was provided by the Heising-Simons Foundation and by the Lawrence Livermore National Laboratory LDRD office. PNNL is a multi-program national laboratory operated for the U.S. DOE by Battelle Memorial Institute under Contract No. DE-AC05-76RL01830. UWA and Swinburne participation is funded by the ARC Centre of Excellence for Engineered Quantum Systems and CE170100009, Dark Matter Particle Physics, CE200100008. The Sheffield group acknowledges support from the UK Science and Technology Facilities Council (STFC) under grants ST/ T006811/1 and ST/X005879/1. CRB is supported by DOE Office of Science, High Energy Physics, Early Career Award (FWP 77794 at PNNL). Chelsea Bartram acknowledges support from the Panofsky Fellowship at SLAC. John Clarke acknowledges support from the U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers.

Why Scan Upward?

- Axions 1 μeV – 1 meV test both pre and post inflationary models
- More constrained region to eliminate theoretical models
- Lower mass searches require very different hardware (lumped circuit element experiments e.g. DMRadio)

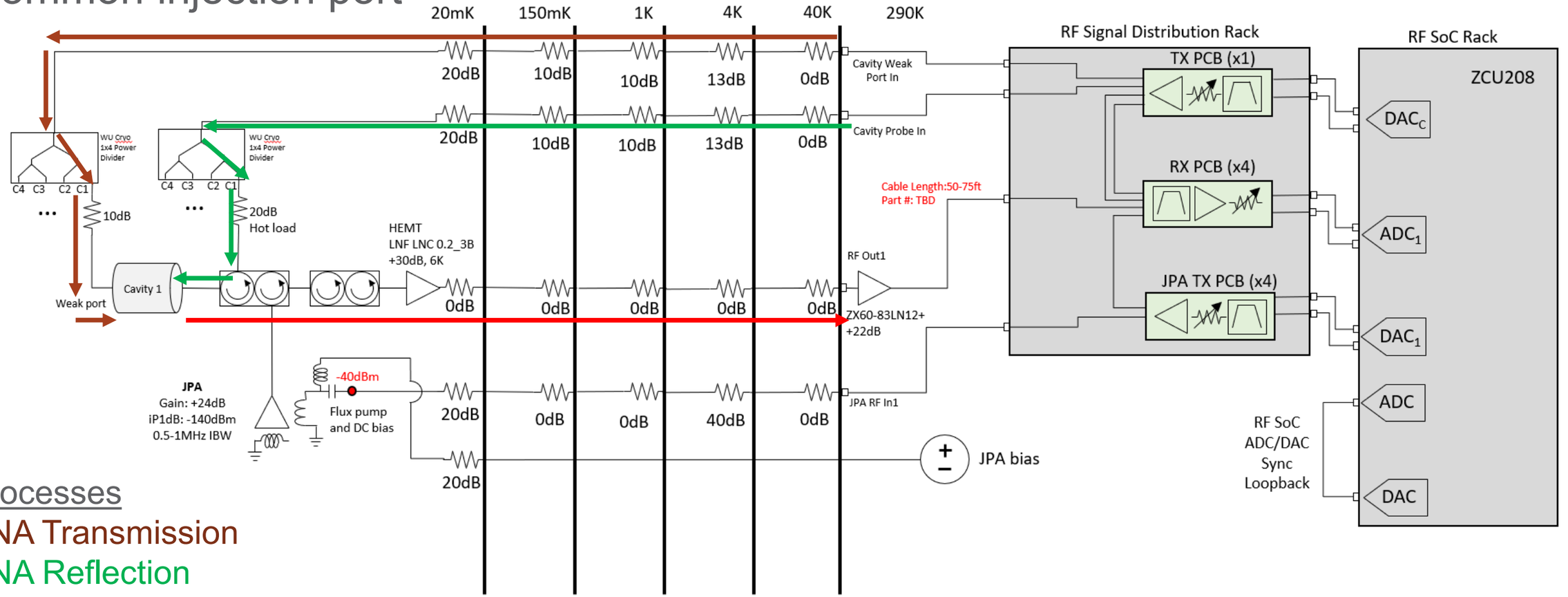


PNNL Work: Run 2 RFSoC

- Four separate RF receivers for each cavity
- combine digitally in analysis
- Common injection port



ZCU208 Board



Processes

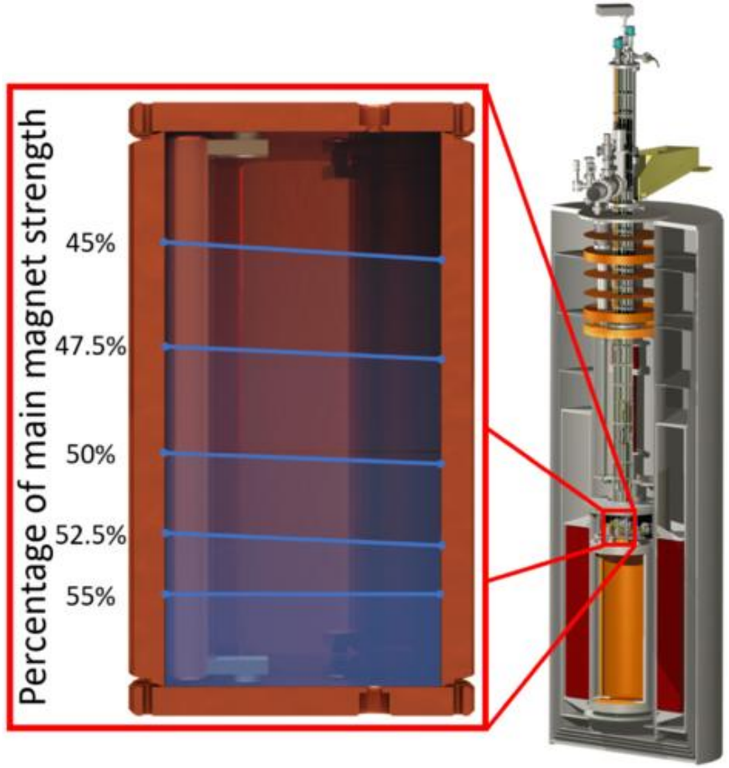
VNA Transmission

VNA Reflection

RF out

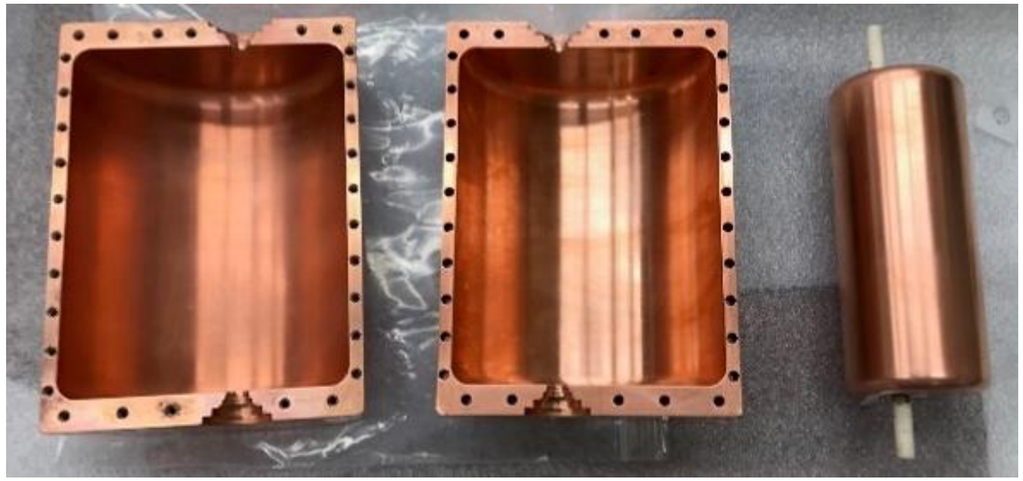
ADMX Sidecar

- Established R&D testbed
- Sits on top of main cavity making use of fridge and B-field
- 3.58 T fringe field during operations
- Emerging Tech used:
  - Piezoelectric Motors (2019)
  - Josephson Travelling Wave Parametric Amplifiers (JTWPA) (2023)
  - Hybrid-Superconducting Cavity (2024)
  - Kinetic Inductance TWPAs (Ongoing)
- **Low Turnover: Bound by main experiments schedule!**



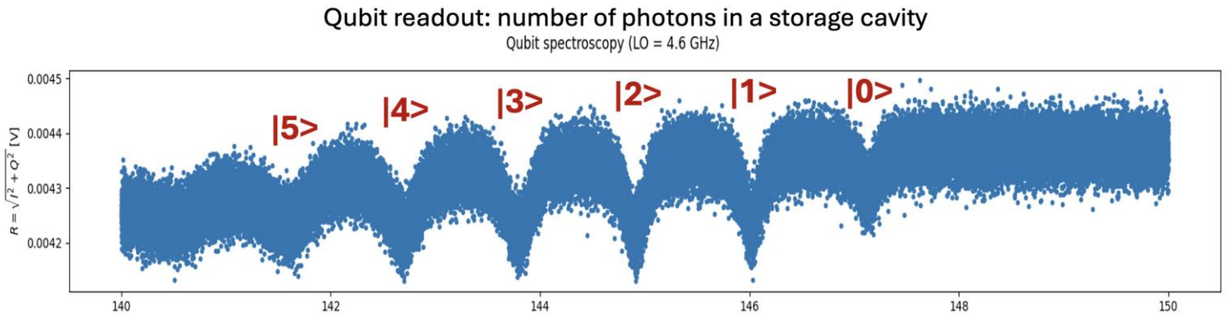


operates at 4-7 GHz
volume of 0.6 L

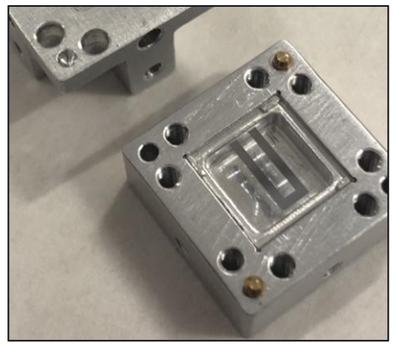


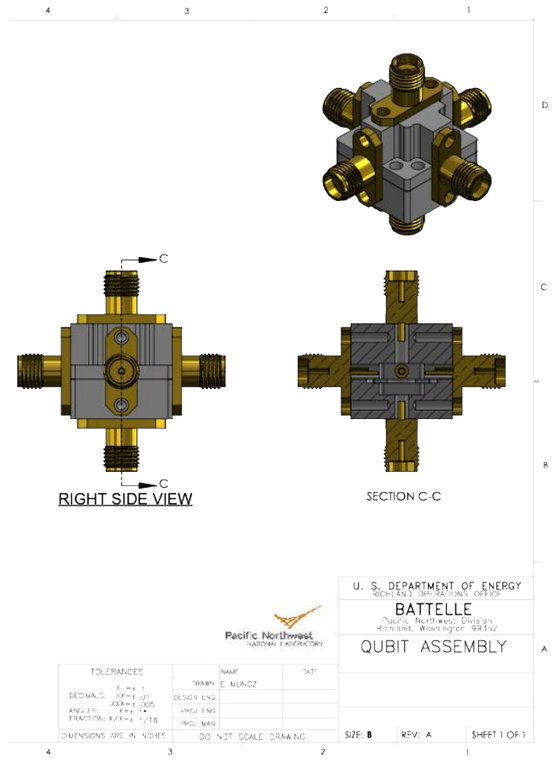
Problem: Increasing Thermal Noise

- Noise temperature at SQL grows with frequency:
  - $\frac{df}{dt} \propto T_{sys}^{-2} \propto f^{-2}$
  - Standard Quantum limit: $T_{sys} = \frac{hf}{k}$
  - Currently not operating at SQL
- Qubit photon counting (ADMX SIDETRAC)
- Quantum Squeezing can mitigate this (VEBAX- Erik Lentz)



Hairpin Qubit design





SIDETRAC Projected Limits

