ADMX Overview and Run Status

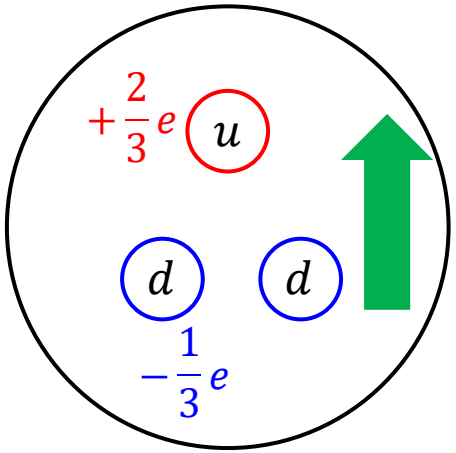
On Kim

University of Washington

CPAD 2026 Workshop

October 21st, 2026

Strong CP Problem



Neutron

Electric dipole moment

$$d_n^{\text{expected}} \approx \mathcal{O}(10^{-16})\ e \cdot \text{cm}$$

$$\left|d_n^{\text{measured}}\right| \lesssim 10^{-26}\ e \cdot \text{cm}$$

10 orders of magnitude!

Dark Matter Problem



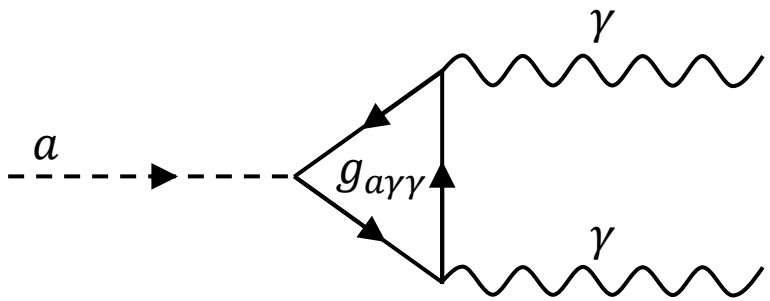
Image: NASA, ESA, CSA, STScI, CXC; Science: James Jee (Yonsei University, UC Davis), Sangjun Cha (Yonsei University), Kyle Finner (Caltech/IPAC)



Axion

Axion–Photon Coupling

- Axion decays into two photons: $\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$

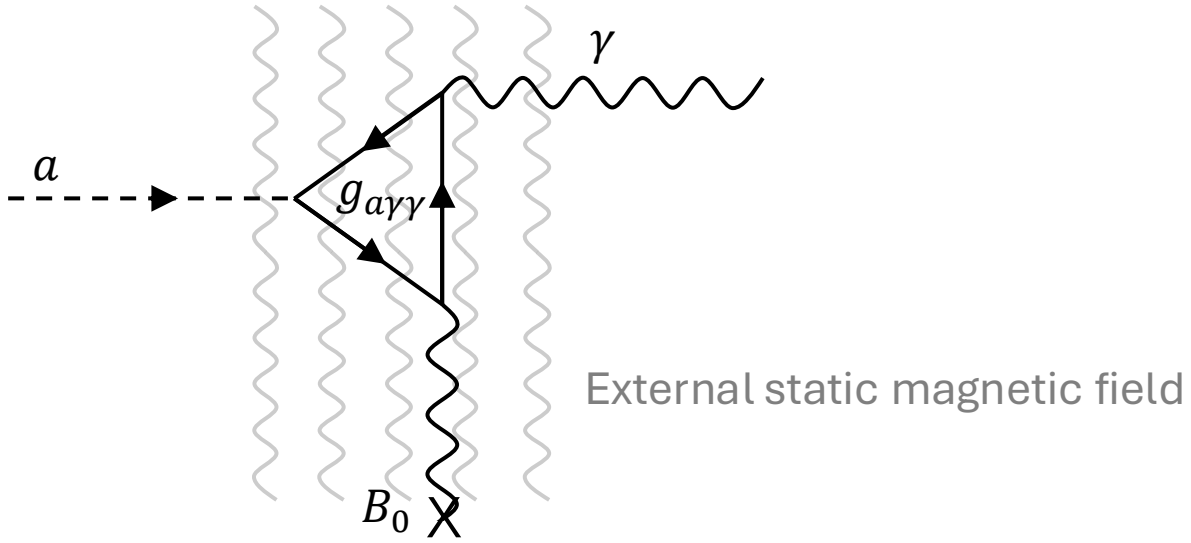


- For a μeV-scale QCD axion, spontaneous two-photon decay lifetime is far longer than the age of the Universe.

Axion–Photon Coupling

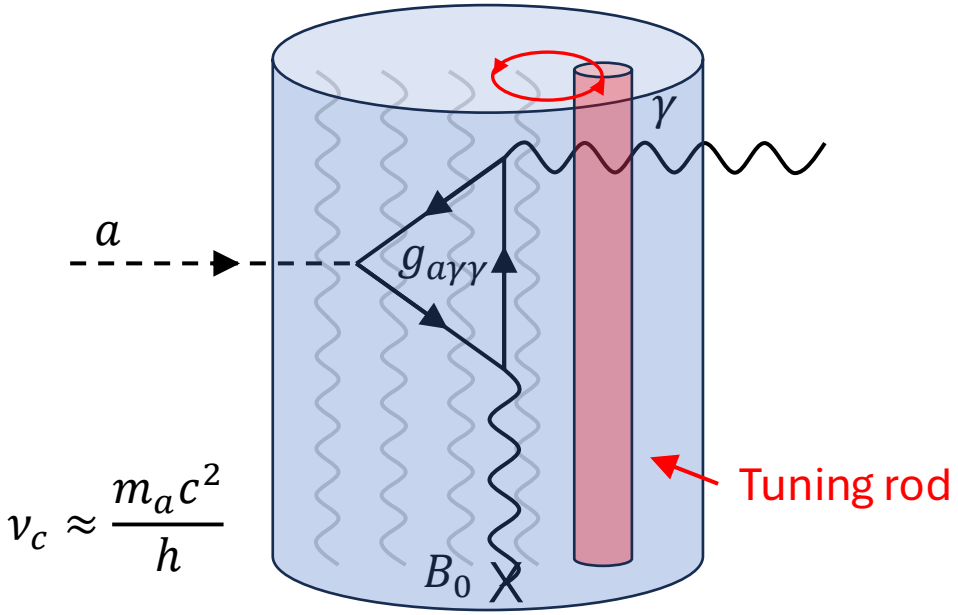
- Instead, we can convert axions into photons in a strong static magnetic field.

Inverse Primakoff process



Microwave Cavity Haloscope

- A high-Q microwave cavity resonantly enhances axion–photon conversion [PRL **51**,1415 (1983)].



- Since we don't know the axion mass *a priori*, the cavity must be tunable.

ADMX “insert”

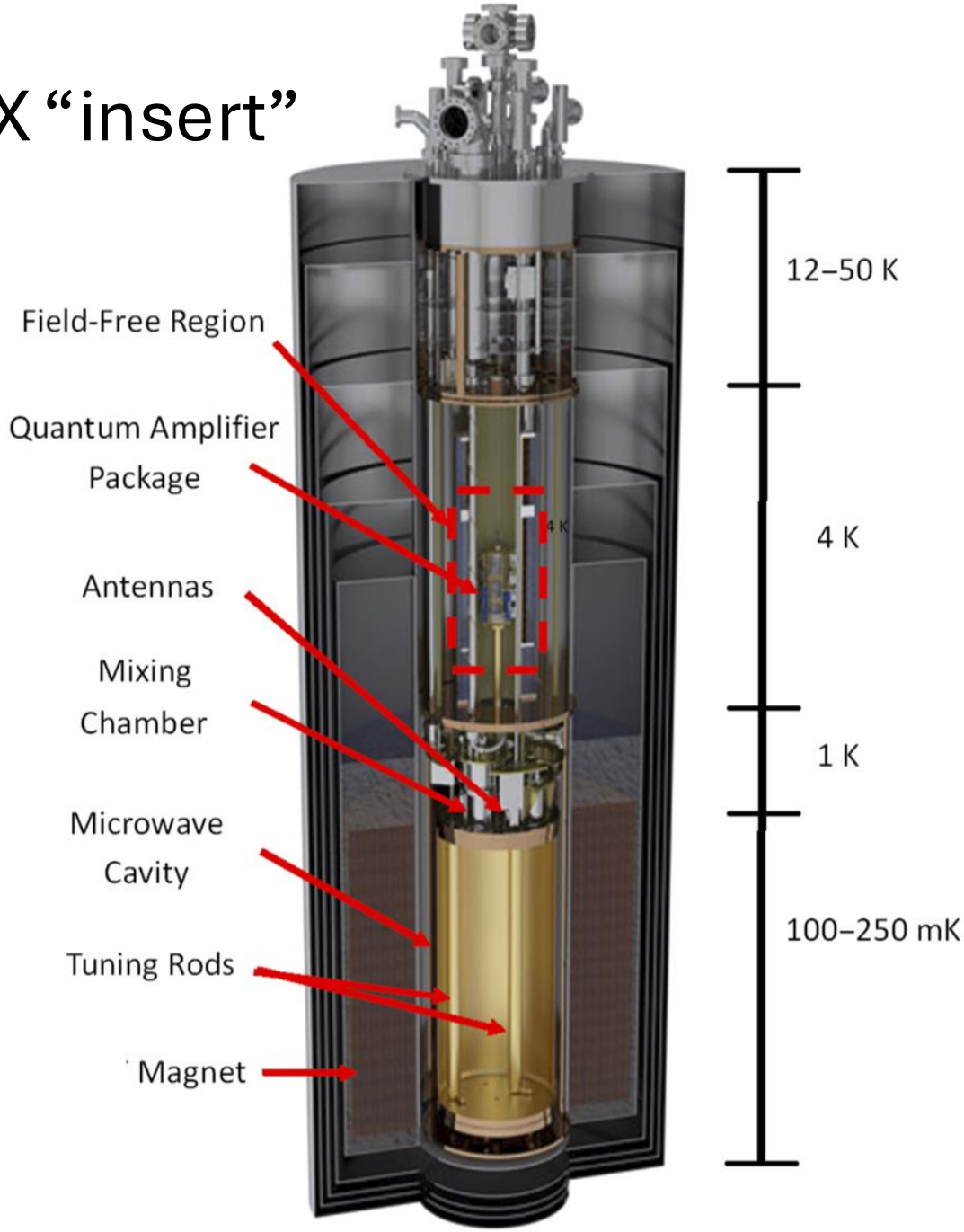
- 7.6 T magnet with a roughly 0.6 m bore diameter, >1 MJ stored energy.

Cavity and tuning rod



Run 1D

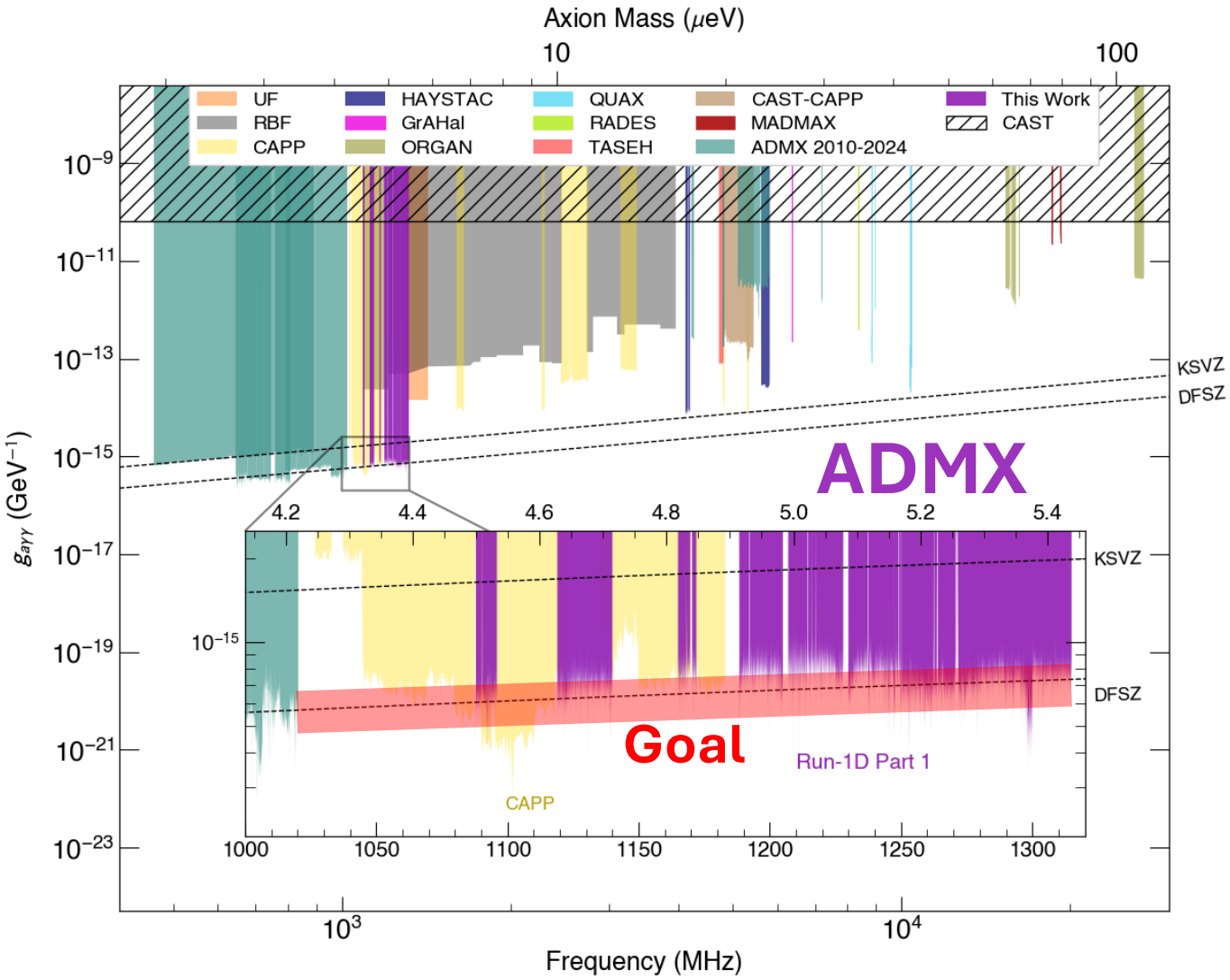




$g_{a\gamma\gamma}$ Parameter Space

- $g_{a\gamma\gamma}$ is axion–photon coupling constant.
- Benchmark QCD axion models: KSVZ and DFSZ.
- Current physics target: achieve DFSZ sensitivity for about 1.0–1.4 GHz range.
- To reach the DFSZ sensitivity, we must know the signal power and noise fluctuation level precisely.

(ADMX) PRL **135**, 191001 (2025)



Signal Power

- On cavity resonance, the expected axion signal power is approximately,

$$P_{\mathrm{sig}}^{\mathrm{ADMX}} \approx 10^{-23}\ \mathrm{W} \left(\frac{g_\gamma}{0.36}\right)^2 \left(\frac{\rho_a}{0.45\ \mathrm{GeV/cm^3}}\right) \left(\frac{\nu}{1\ \mathrm{GHz}}\right) \left(\frac{B_0}{7.6\ \mathrm{T}}\right)^2 \left(\frac{V}{106\ \mathrm{L}}\right) \left(\frac{C}{0.4}\right) \left(\frac{Q}{45\ 000}\right)$$

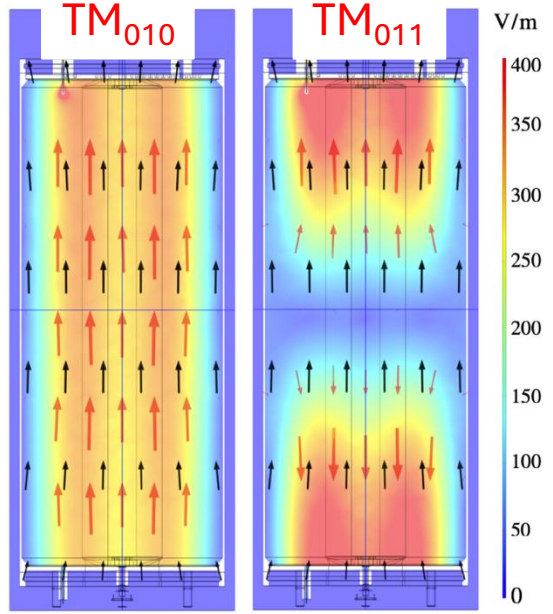
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Input model parameters — Detector parameters

- Large, strong magnet B^2V
- Form factor (mode overlap) C
  Axion couples most strongly to TM_{010} mode in ADMX setup.
- (Loaded) quality factor $Q = \omega U / P_{\mathrm{loss}}$
  $2\pi \times$ stored energy / lost energy per cycle.
- The antenna coupling β is assumed to be around 2.



$C \approx 0.4$ $C \approx 0$

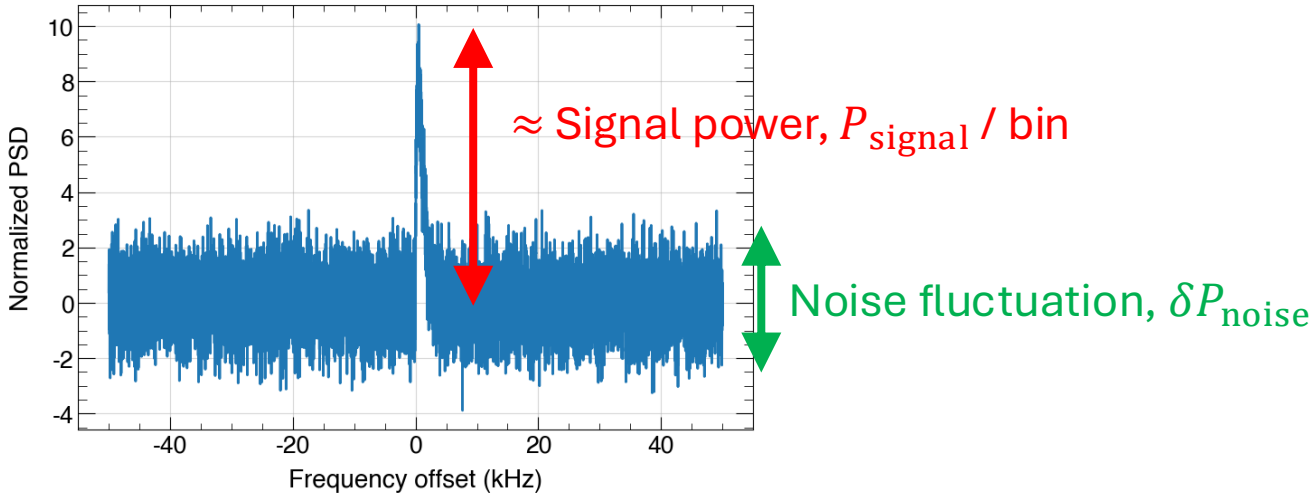
Signal Power

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- The signal power corresponds to only 10–20 photons per second.

- How can we reduce the noise fluctuations to this signal scale?



Noise

- Dicke radiometer equation:

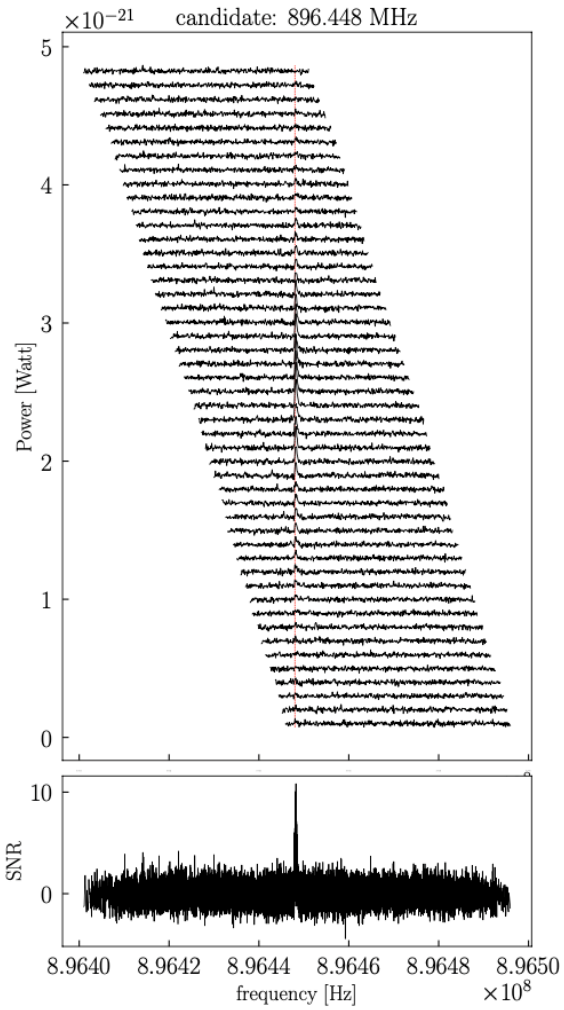
$$\delta P_{\text{noise}} = \frac{P_{\text{noise}}}{\sqrt{\tau\,\Delta\nu}} = k_B T_{\text{sys}} \sqrt{\frac{\Delta\nu}{\tau}} \lesssim 10^{-23}\ \text{W}$$

System noise temperature: ~0.6 K
Resolution bandwidth: 100 Hz
Integration time: 100 s

- For a single scan, we have DFSZ signal-to-noise ratio (SNR) of:

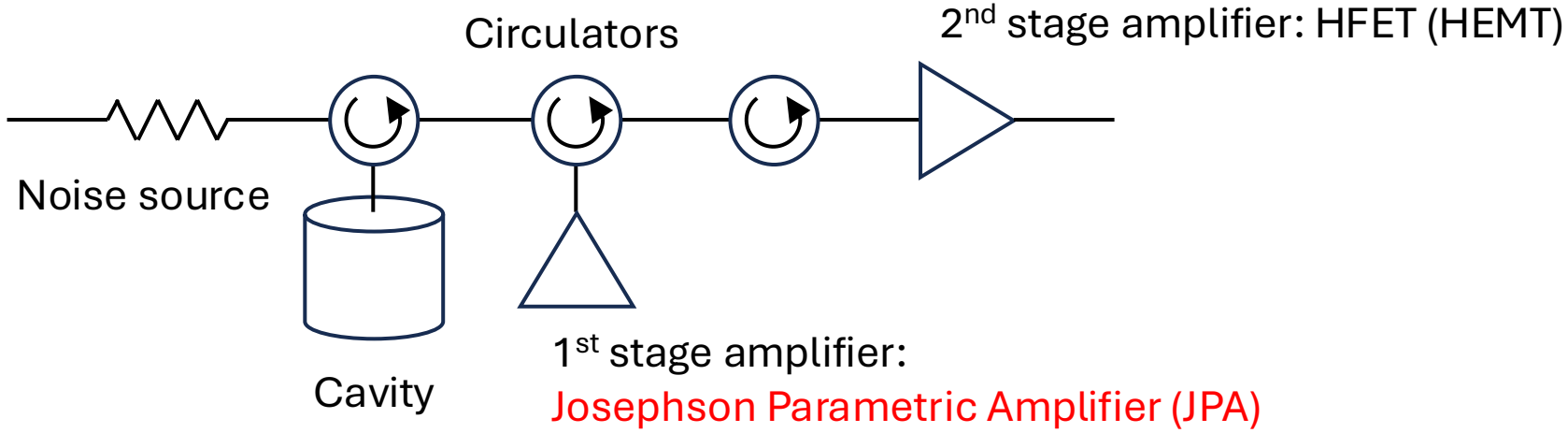
$$\text{SNR} \equiv \frac{P_{\text{signal}}^{\text{DFSZ}}}{\delta P_{\text{noise,1kHz}}} < 1$$

- Reliable exclusion or discovery requires substantially higher SNR.
  → Combine statistics to increase SNR



Cold RF Chain

- The cold RF chain effectively looks as follows:

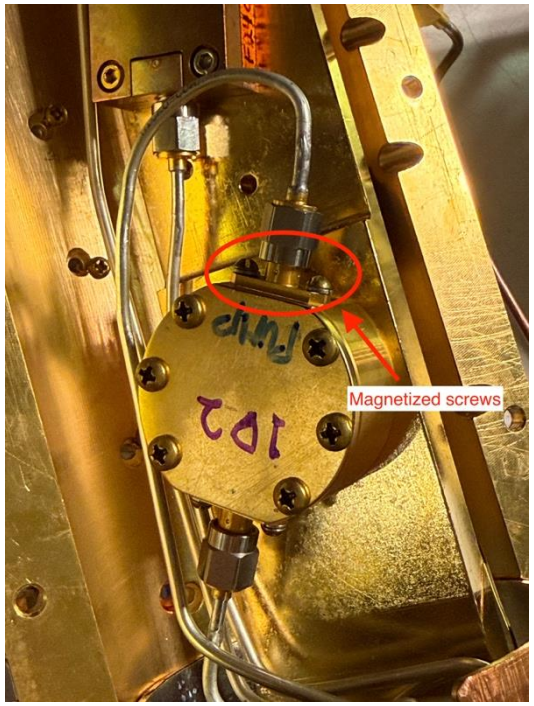


- The cavity physical temperature and the added noise of the first stage amplifier are the dominant factors that determine the system noise temperature.

Listen to Kieran's talk (next talk) for more details on our JPA and noise calibrations

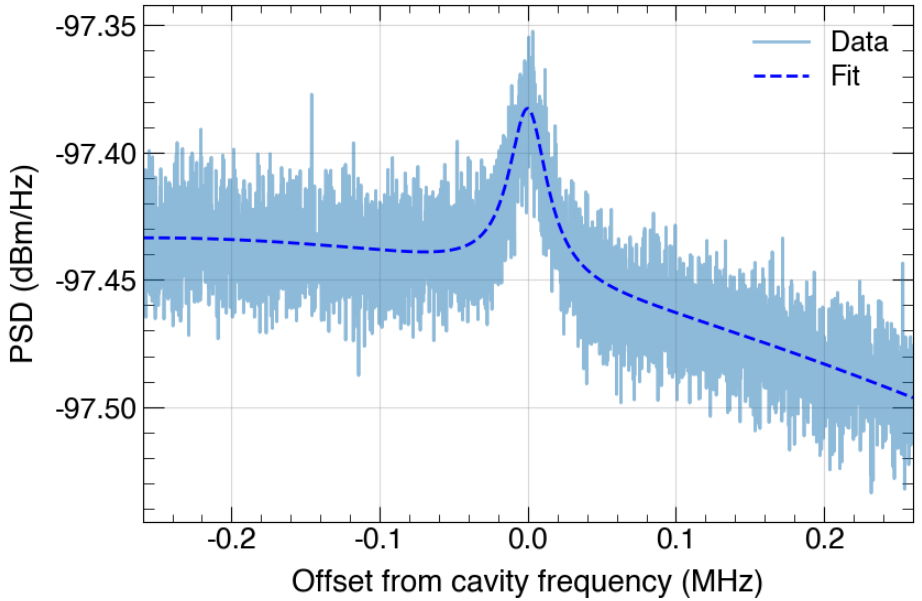
Challenges

Magnet quench (Jan. 2026)
- magnetized the JPA. After repair and other upgrades, data taking in June 2026.

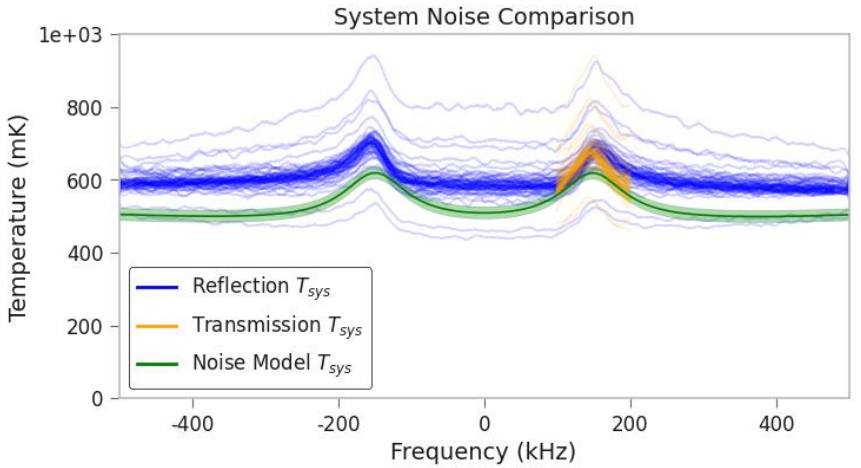


Fixed

Hot cavity
- Cavity effective temperature appears hotter than the temperature sensor. Typically indicates hot-rod problem.



Noise model discrepancy
- Discrepancies between the noise model and the SNRI measurements can be due to the cavity–JPA interaction.

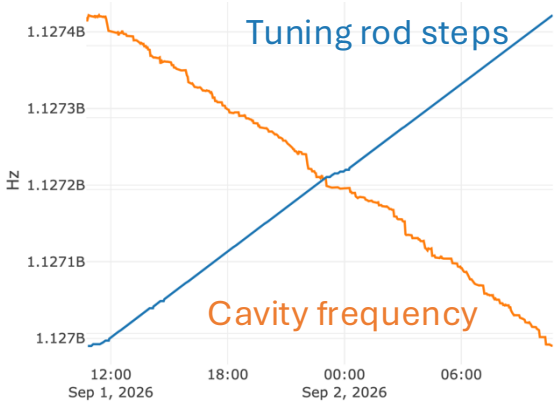


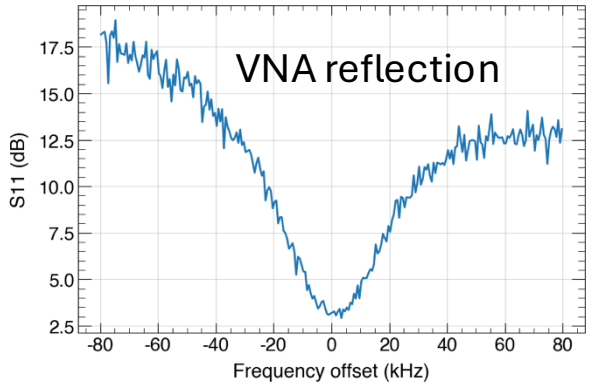
Working on model analysis and upgrade planning

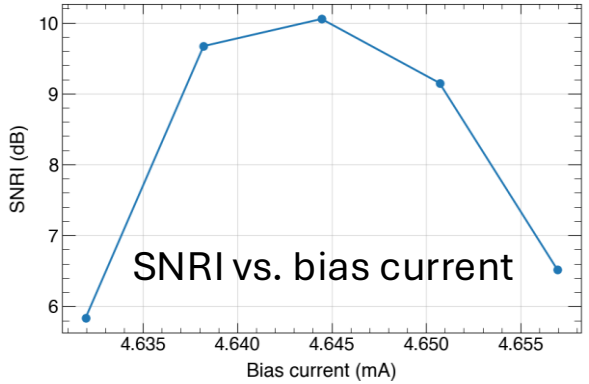
Data Taking

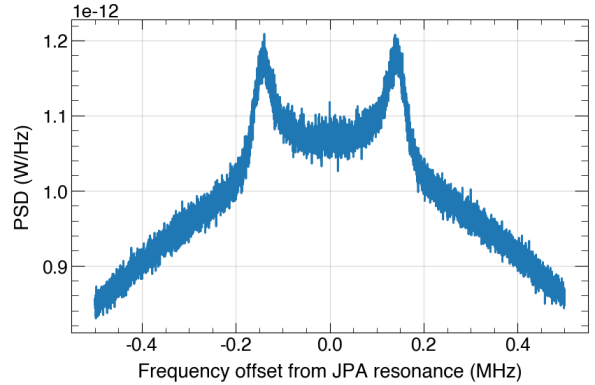
- Each scan follows this sequence:

Tuning → Cavity characterization → JPA calibration and tuning → Digitization







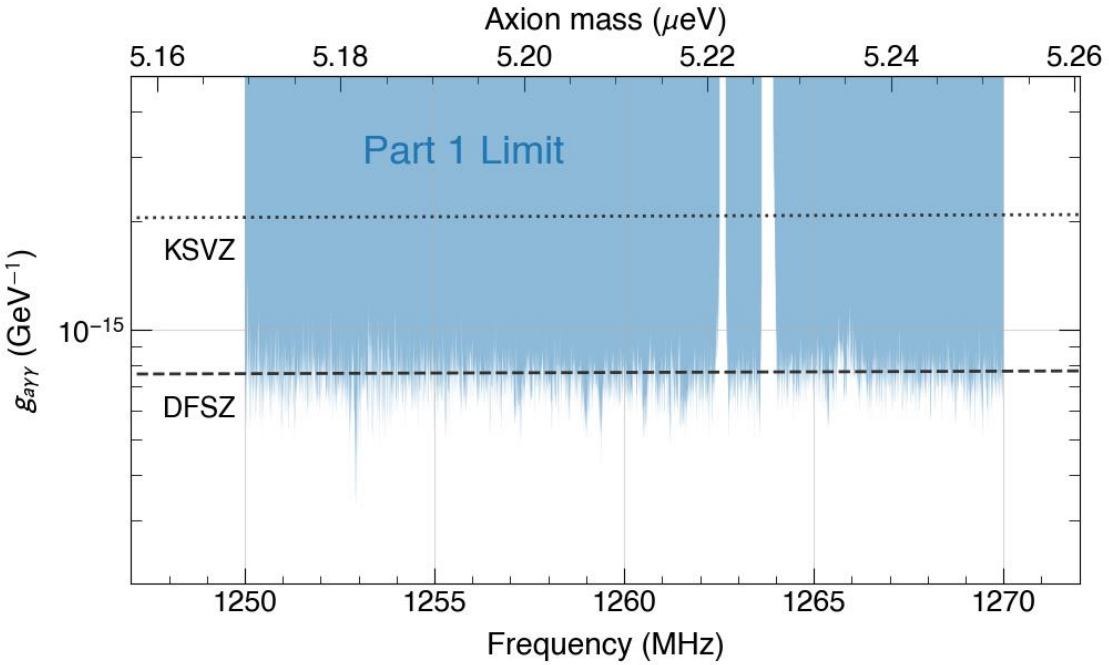


- Tune the cavity resonance
- Measure cavity resonance, Q-factor, antenna coupling
- Monitor mode crossing
- Measure SNRI
- Periodically re-bias JPA
- 100-second digitization

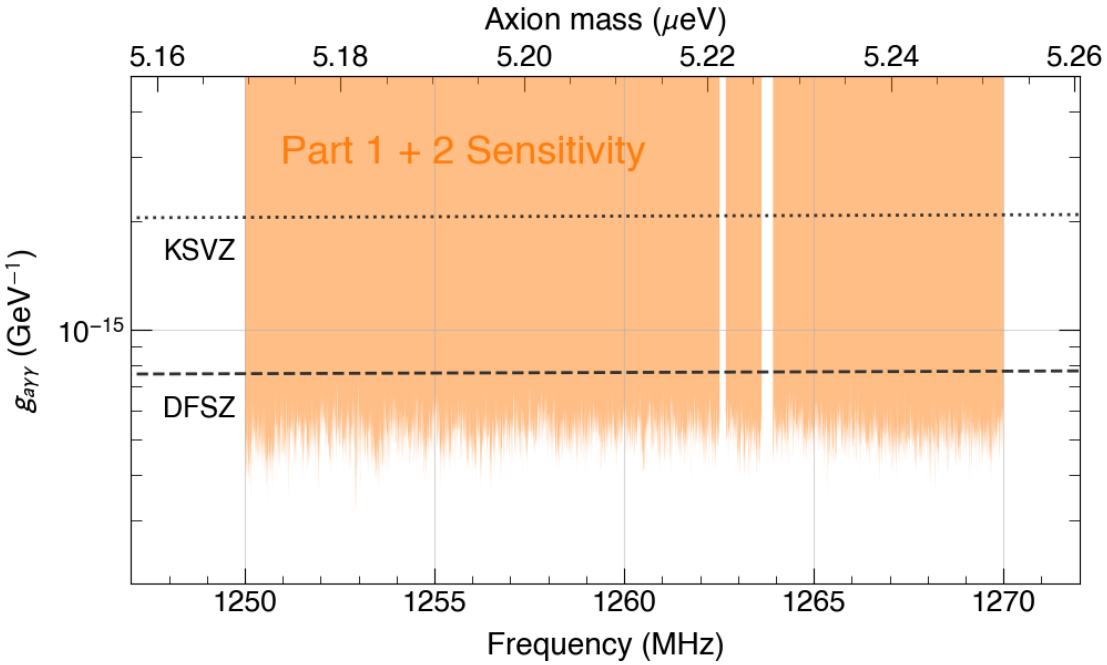
Preliminary Result

- Highlighting our first frequency interval: 1250–1270 MHz.

Published in 2025 (not quite DFSZ)



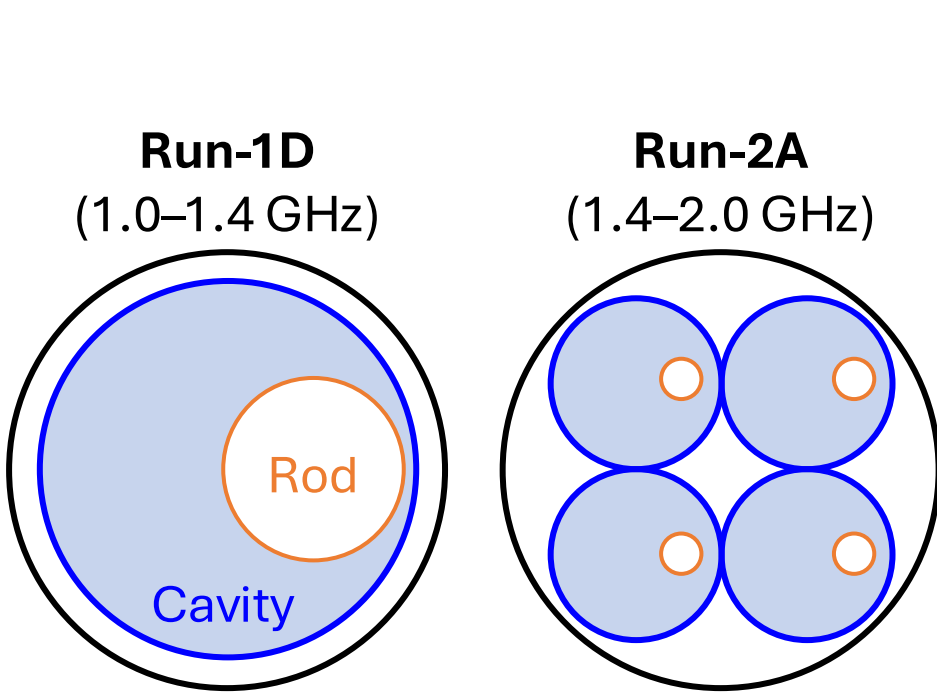
Preliminary

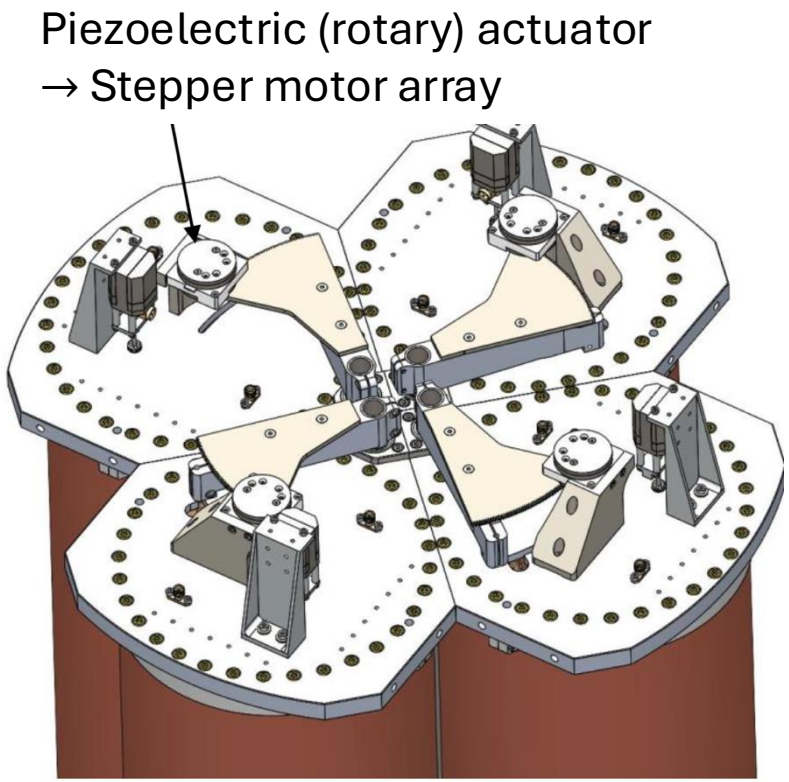


- Assuming axion constitute the entirety of the local dark matter (DM) halo, and at a DFSZ coupling, we excluded the DM density (previously) 0.49 GeV/cm^3 → (now) 0.22 GeV/cm^3.

Looking Forward: Run-2A

- We will have four cavity array to search for higher frequency.
- Cavity and 4K teststand at Fermilab.
- Ongoing: commissioning of amplifier chain and dark photon search.







@Fermilab

Summary

- ADMX searches for axion dark matter at the DFSZ sensitivity.
  - Microwave cavity resonator(s) as our coherent detector.
  - Employs quantum amplifier package (such as JPA) to achieve quantum-limited noise.

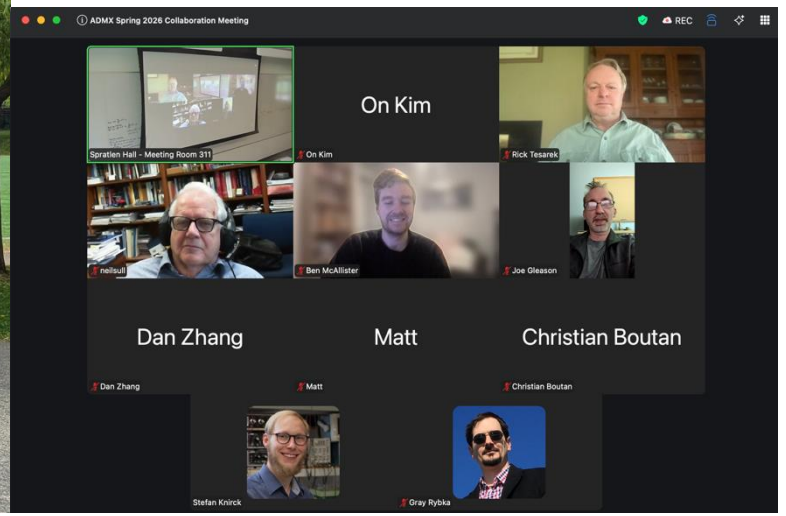
- Currently, we are taking data over 1.0–1.4 GHz range ensuring the DFSZ sensitivity.

- The next run (2A) will be using four cavity array to maximize the signal power in a given volume.

Thank you for your attention!



ADMX
AXION DARK MATTER EXPERIMENT



Acknowledgements

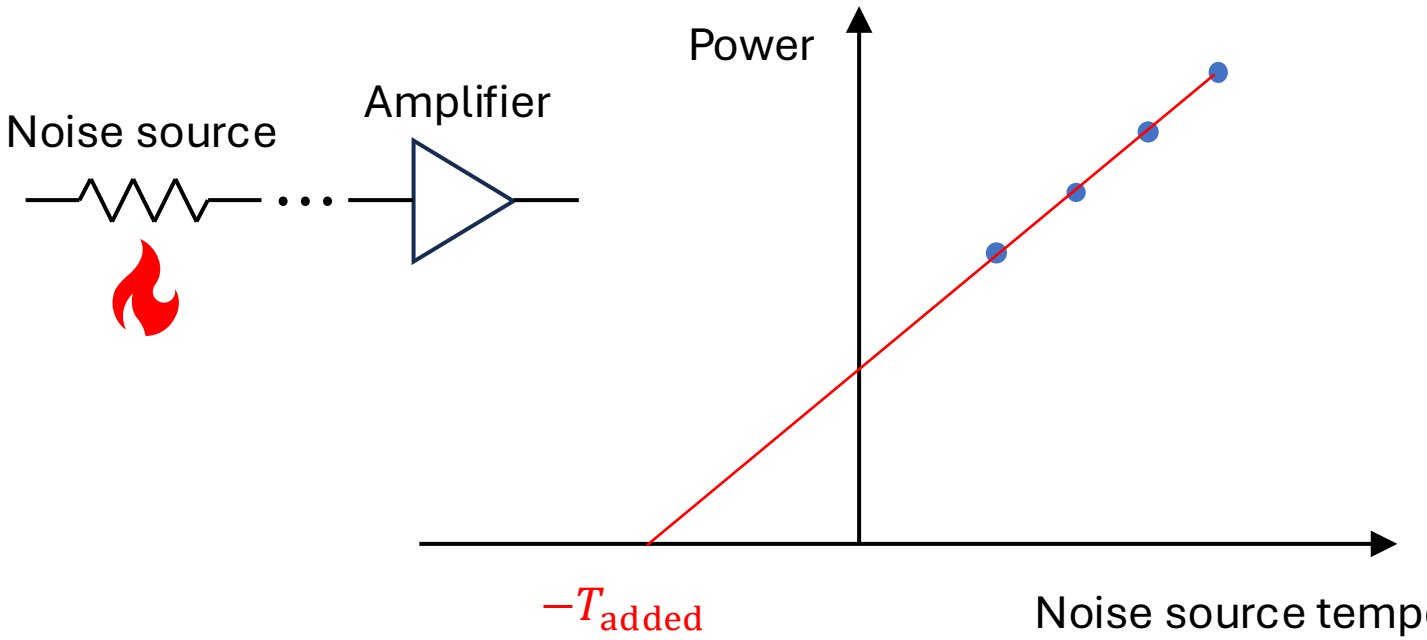
This work is supported by U.S. Department of Energy through Awards No DE-SC0009800, No. DE-SC0009723, No. DE-SC0010296, No. DE-SC0010280, No. DE-SC0011665, No. DEFG02-97ER41029, No. DE-FG02-96ER40956, No. DE-AC52-07NA27344, No. DE-C03-76SF00098, No. DE-SC-0022148 and No. DE-SC0017987. Fermilab is a U.S. 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.

Backup

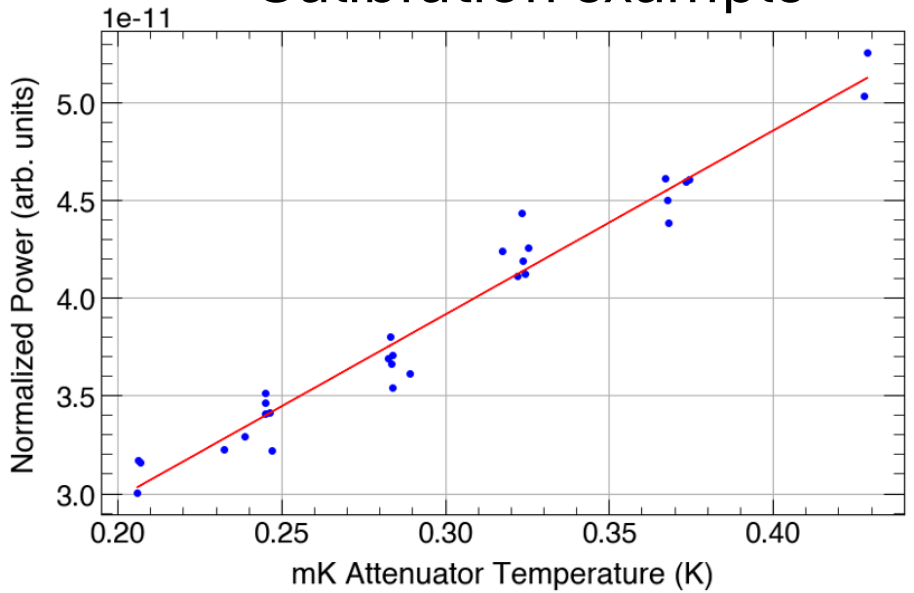
*Details of ADMX noise calibration can be found in [PRD **111**, 092012 (2025)]

Noise Calibration

- We heat a noise source and measure output power versus source temperature.



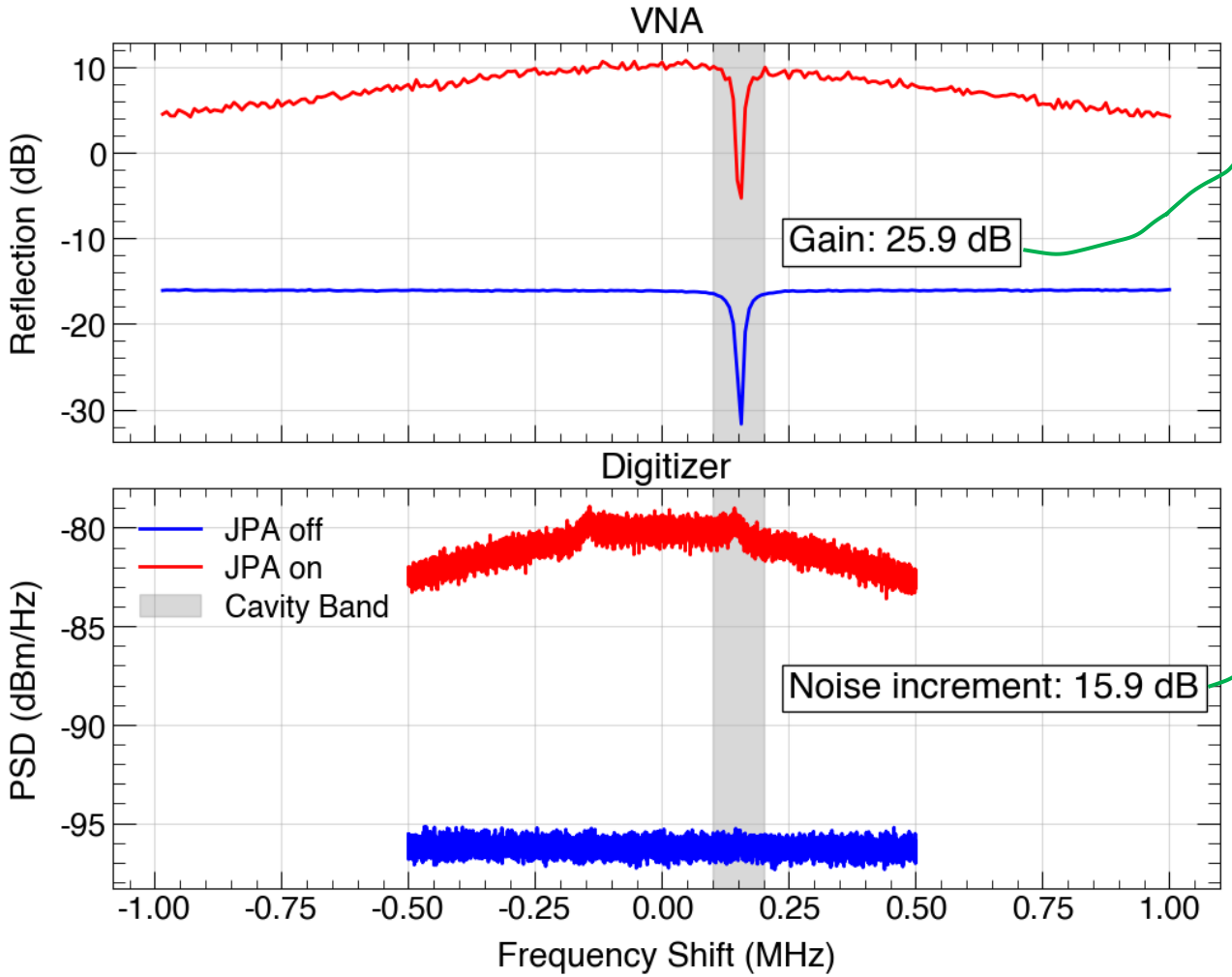
Calibration example



- The narrowband JPA must be retuned with frequency. Repeating a full thermal calibration at every setting is impractical.

Signal-to-Noise Ratio Improvement (SNRI)

- We measure the SNR improvement with the JPA on versus off.



Already-calibrated (broadband)

$$\mathrm{SNRI} = \frac{G}{P_{\mathrm{on}}/P_{\mathrm{off}}} = \frac{T_{\mathrm{HFET}}^{\mathrm{eff}}}{T_{\mathrm{sys}}}$$

SNRI is $25.9 - 15.9 = 10.0$ dB in this example

$$T_{\mathrm{sys}} = \frac{T_{\mathrm{HFET}}^{\mathrm{eff}}}{\mathrm{SNRI}}$$

Strong CP Problem

- QCD Lagrangian admits the CP-odd term:

$$\mathcal{L} \supset \bar{\theta} \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

- It introduces a nonzero neutron electric dipole moment (nEDM):

$$d_n \approx \mathcal{O}(10^{-16}) \times \bar{\theta} \ \ e \cdot \mathrm{cm}$$

- The 2020 neutron EDM measurement gives [PRL **124**, 081803 (2020)]:

$$|d_n| < 1.8 \times 10^{-26} \ e \cdot \mathrm{cm} \ (90\% \ \mathrm{C.L.})$$

- It implies

$$\left|\bar{\theta}\right| \lesssim 10^{-10}$$

- But $\bar{\theta}$ is a dimensionless angular parameter, whose natural domain is $-\pi < \bar{\theta} \leq \pi$. The Standard Model does not provide an explanation for this small value.

Strong CP problem: Why is the physical CP-violating angle so small?

The Peccei-Quinn Solution

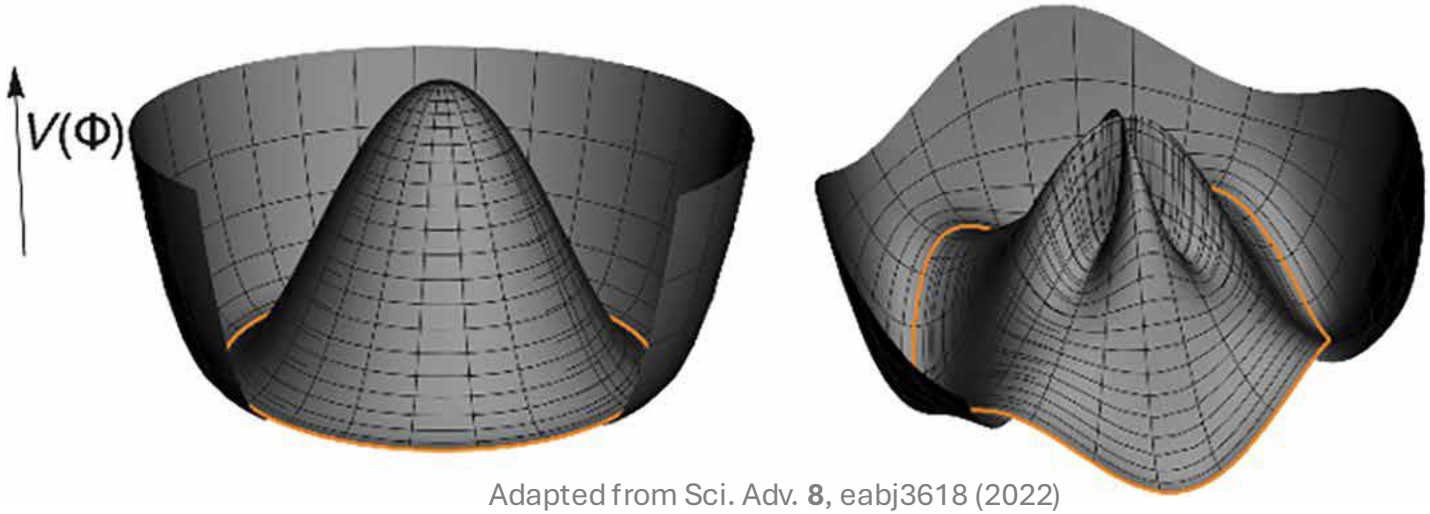
- Spontaneous breaking of the Peccei–Quinn symmetry introduces the axion field $a(x)$, making the effective CP angle dynamical [PRL **38**, 1440 (1977)].

$$\theta_{\mathrm{mis}} \equiv \bar{\theta} + \frac{a(x)}{f_a}$$ axion field

- θ_{mis} can take any value when universe is hot enough, but after the QCD transition, the axion "rolls down" the potential and θ_{mis} relaxes toward zero and oscillates about the minimum.

Before QCD transition

After QCD transition



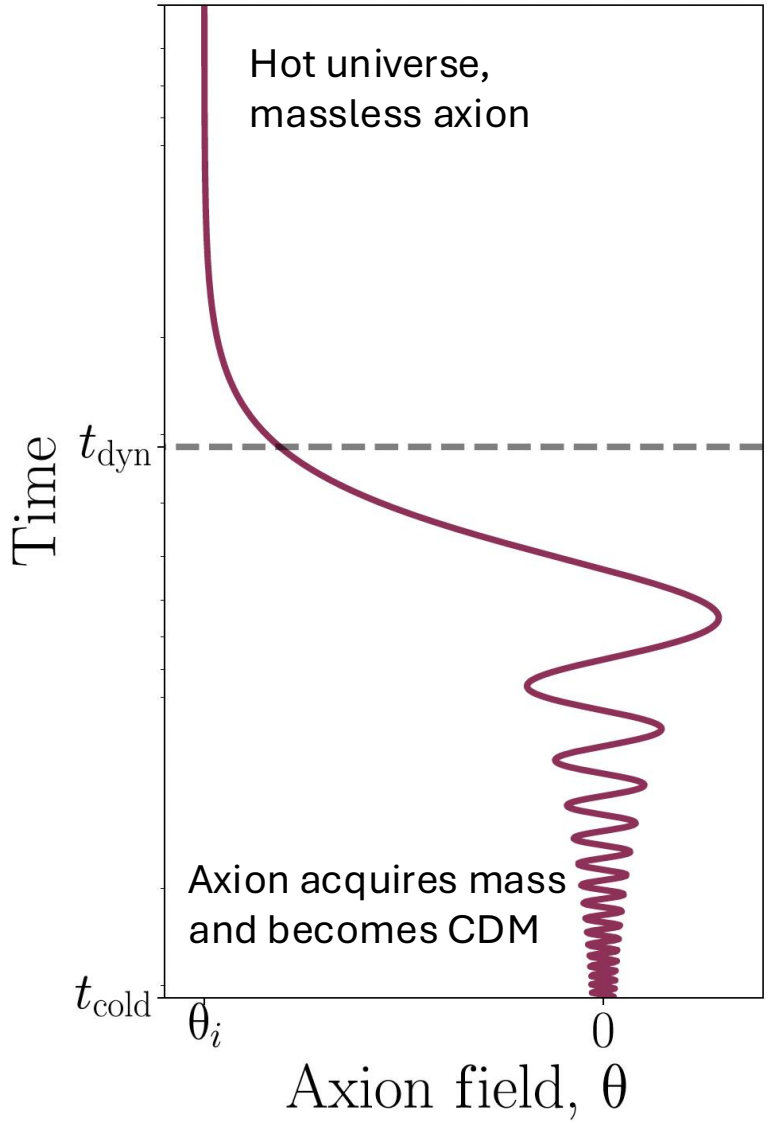
Adapted from Sci. Adv. **8**, eabj3618 (2022)

Axion Dark Matter

- Axions can be produced nonthermally as coherent field oscillations.
  - Negligible initial momentum → **cold**
  - Extremely weak interactions → **long-lived**
  - Adequate misalignment (or topological defects) → observed **DM abundance**

- Under standard cosmological assumptions, QCD axion dark matter naturally lies in the μeV–sub-meV regime.

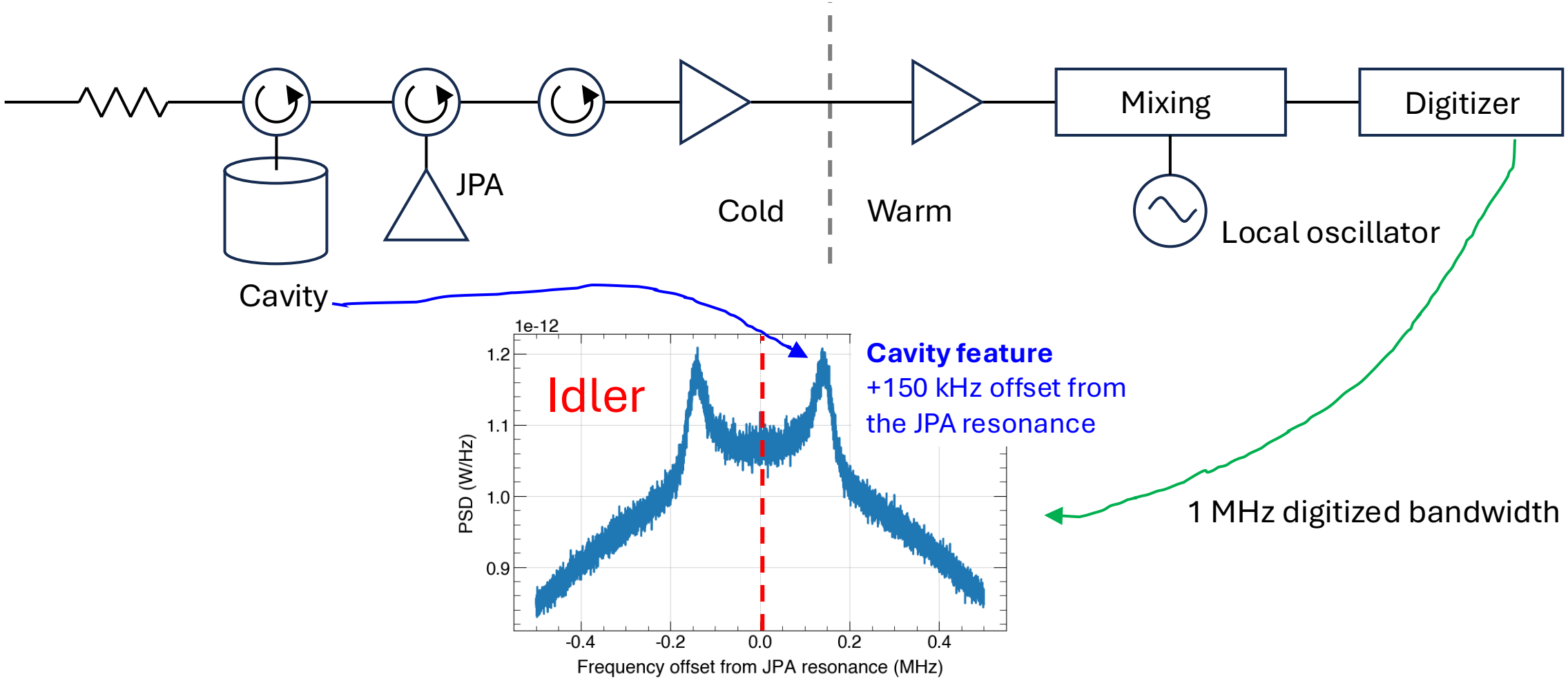
- 1 μeV → ~240 MHz, turning the search into a measurement of an oscillating field of a "microwave" frequency.



Adapted from Sci. Adv. **8**, eabj3618 (2022)

Receiver Chain

- The digitizer records a band containing the cavity feature and its idler image produced by the JPA.



Analysis Pipeline

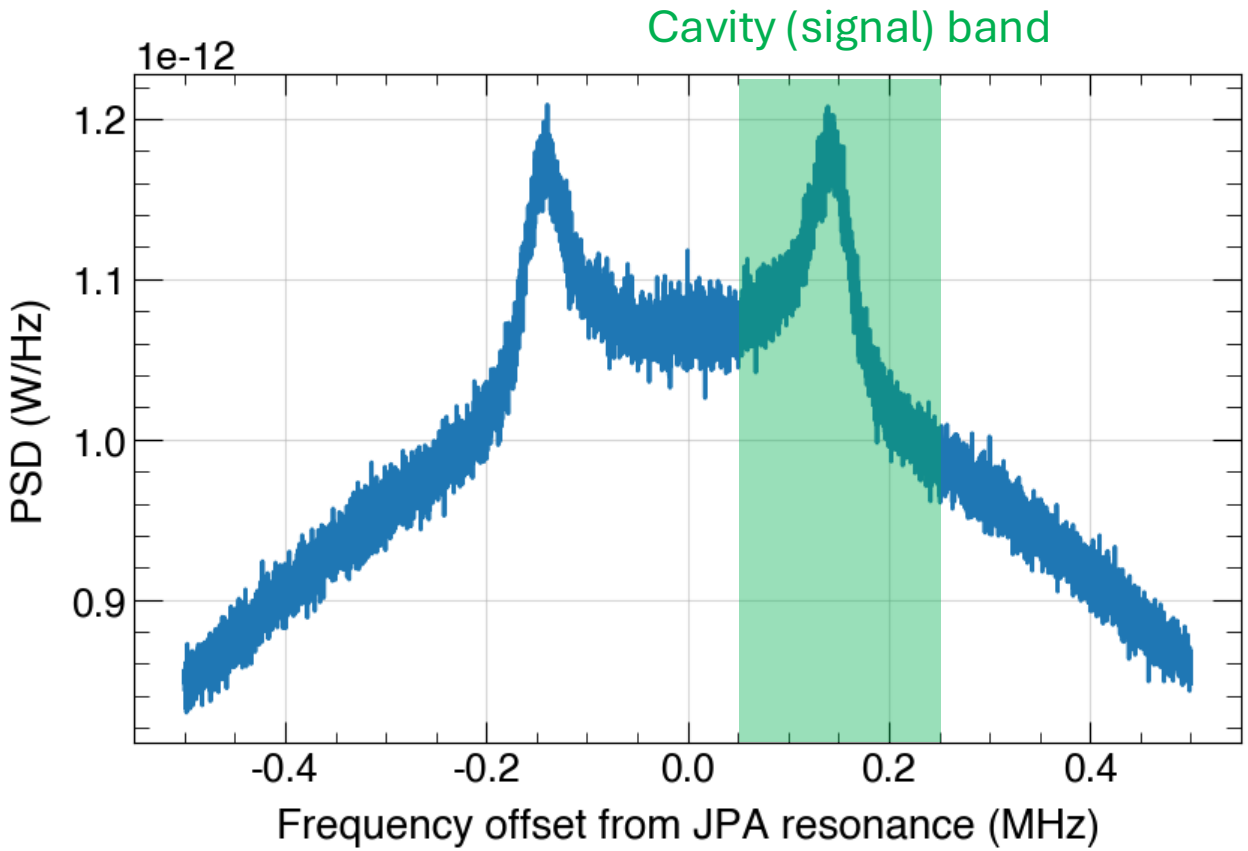


Analysis Pipeline

DQC-passed raw spectra → Baseline removal → Response and DFSZ normalization → Axion lineshape fit → Grand spectrum → Candidate rescan → Discovery or exclusion

P_{raw}

- Apply data-quality cuts and retain the $\pm$ 100 kHz band around the cavity resonance.



Analysis Pipeline

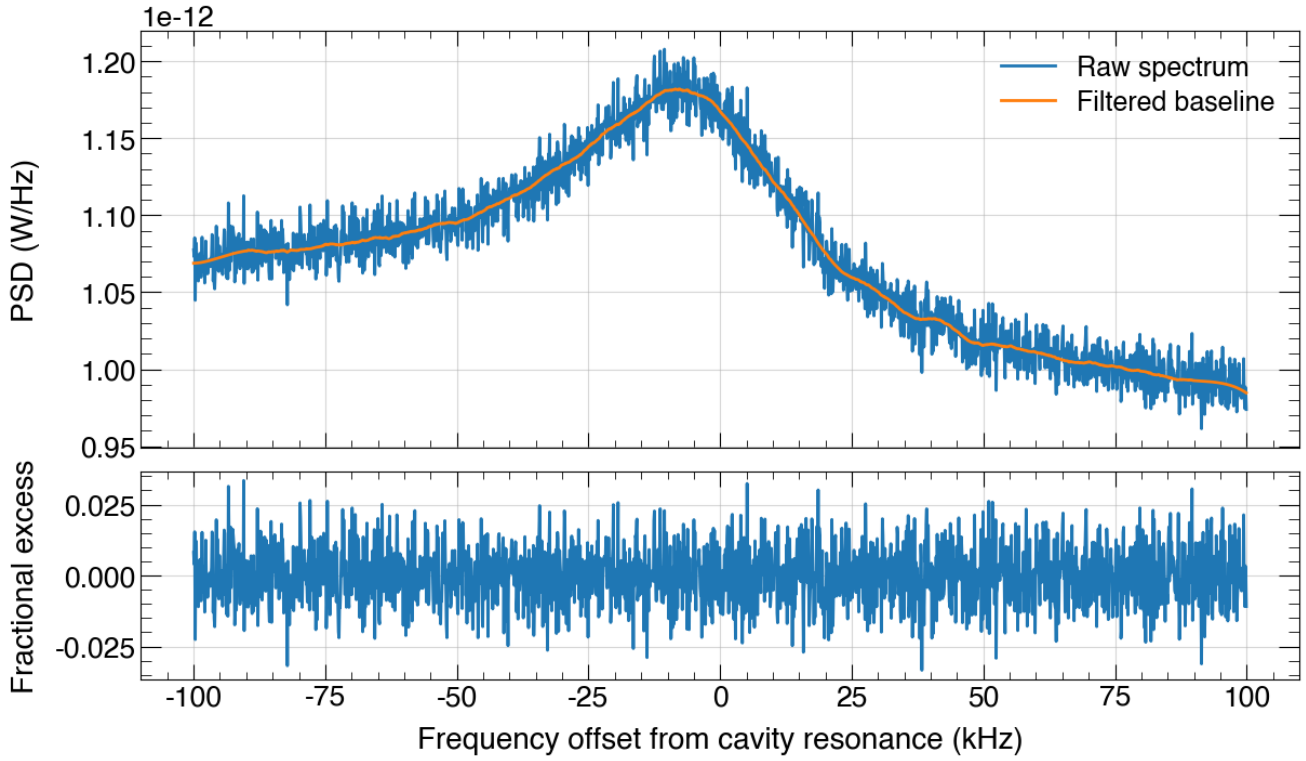
DQC-passed raw spectra → **Baseline removal** → Response and DFSZ normalization → Axion lineshape fit → Grand spectrum → Candidate rescan → Discovery or exclusion

P_{raw} $\quad x = \frac{P_{\mathrm{raw}}}{B} - 1$

- We conventionally estimate the receiver baseline with a Savitzky–Golay smoothing filter.
- Define the fractional excess x:

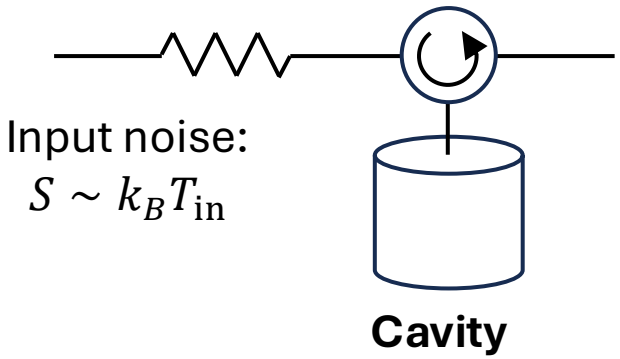
$$x = \frac{P_{\mathrm{raw}}}{B} - 1$$

- This procedure could attenuate the narrow axion signal.
- Can a physical baseline model preserve more of the axion signal?



Feed-forward Model: Cavity

- The temperature contrast sets whether the cavity feature is a peak or a dip.



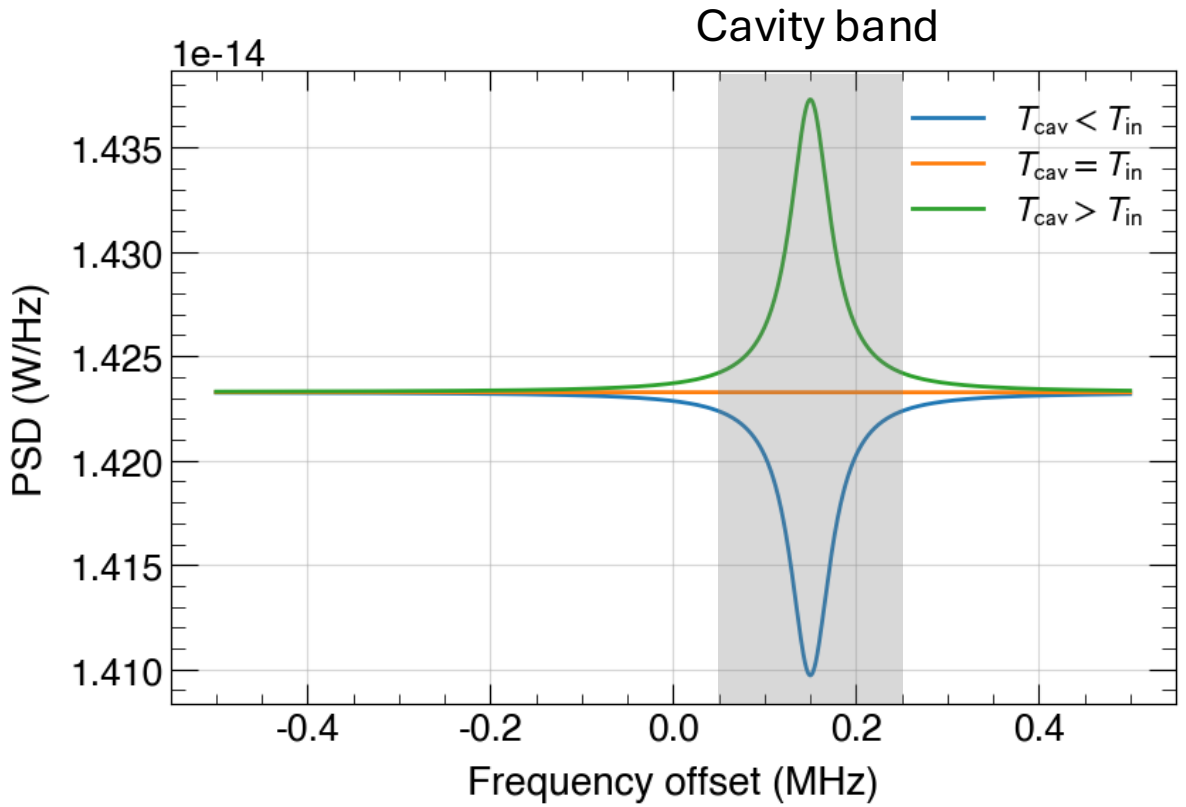
Near-perfect reflector ($R \approx 1$), off-resonance
Near-perfect absorber ($R \approx 0$), on-resonance

(near critical coupling, $\beta = 1$)

($R \equiv |\Gamma|^2$ is the cavity reflectance)

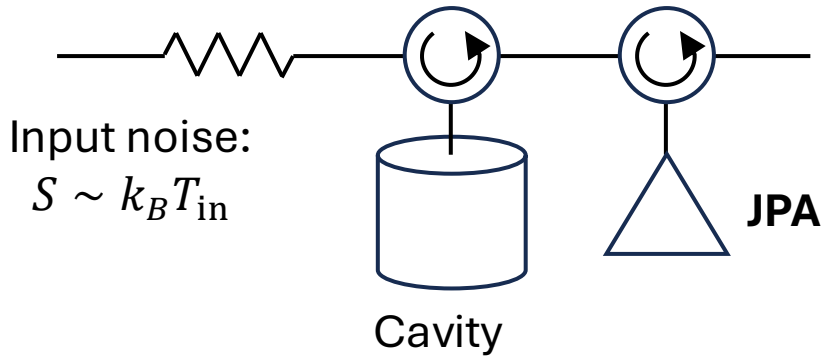
Cavity output:

$$S(\omega) \sim R(\omega)\, k_B T_{\mathrm{in}} + \big(1 - R(\omega)\big)\, k_B T_{\mathrm{cav}}$$



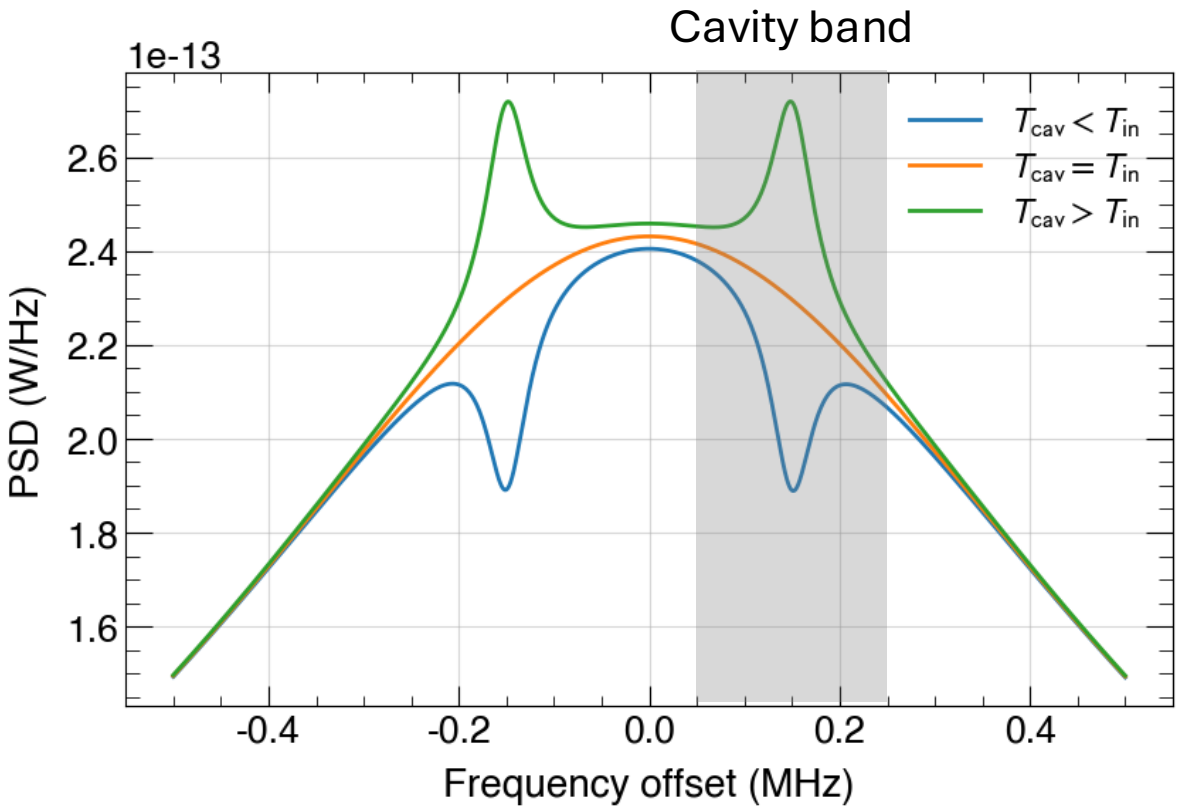
Feed-forward Model: JPA

- The JPA mixes the signal and idler bands, producing a mirrored cavity feature.



JPA output:

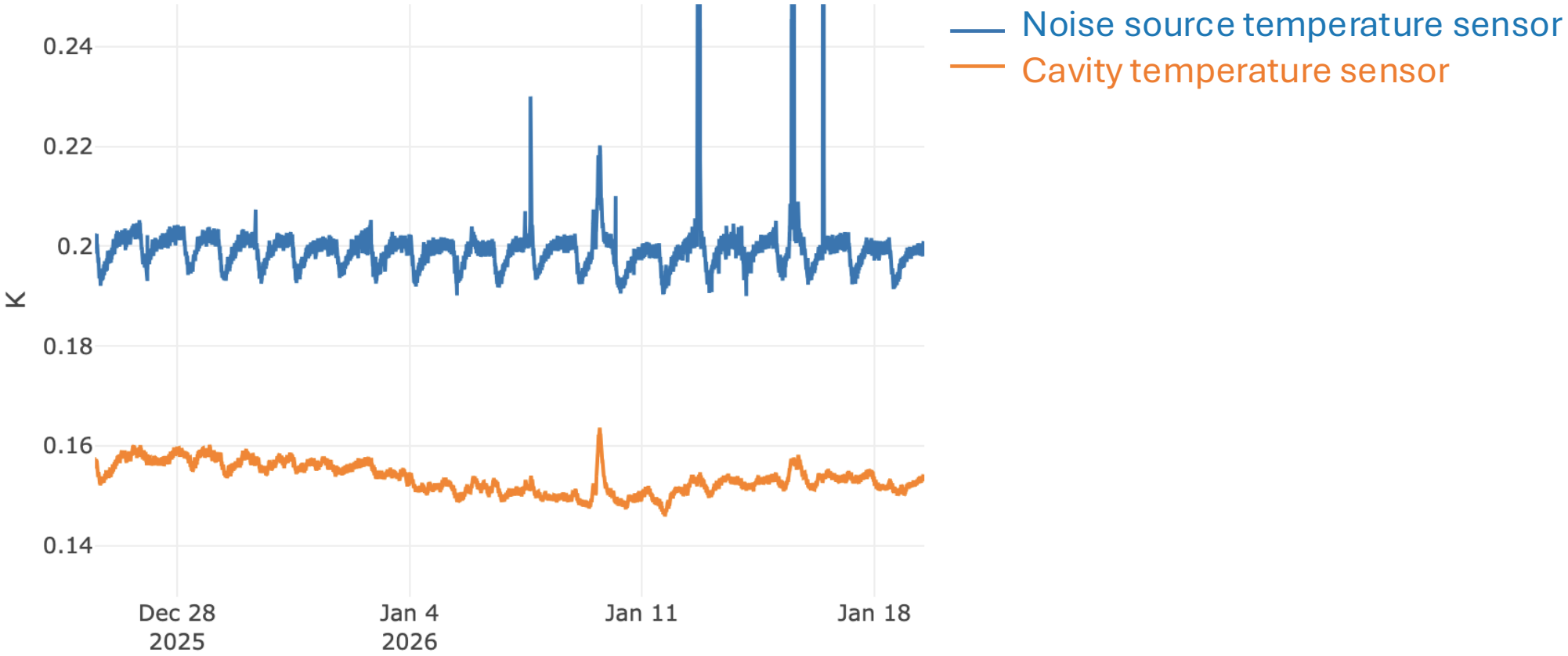
$$S(\omega) \sim G(\omega)\, S_{\text{cav}}(\omega) + \underbrace{G_i(\omega_i)\, S_{\text{cav}}(\omega_i)}_{\text{idler}}$$



- A hotter cavity reproduces the broad cat-ear structure in the forward model.

Hot Cavity

- A cavity hotter than the input noise source can produce a peak, but the cavity sensor reads a lower temperature.



Hot Rod

- A simple hypothesis: poor thermalization leaves the tuning rod hotter than the cavity walls.



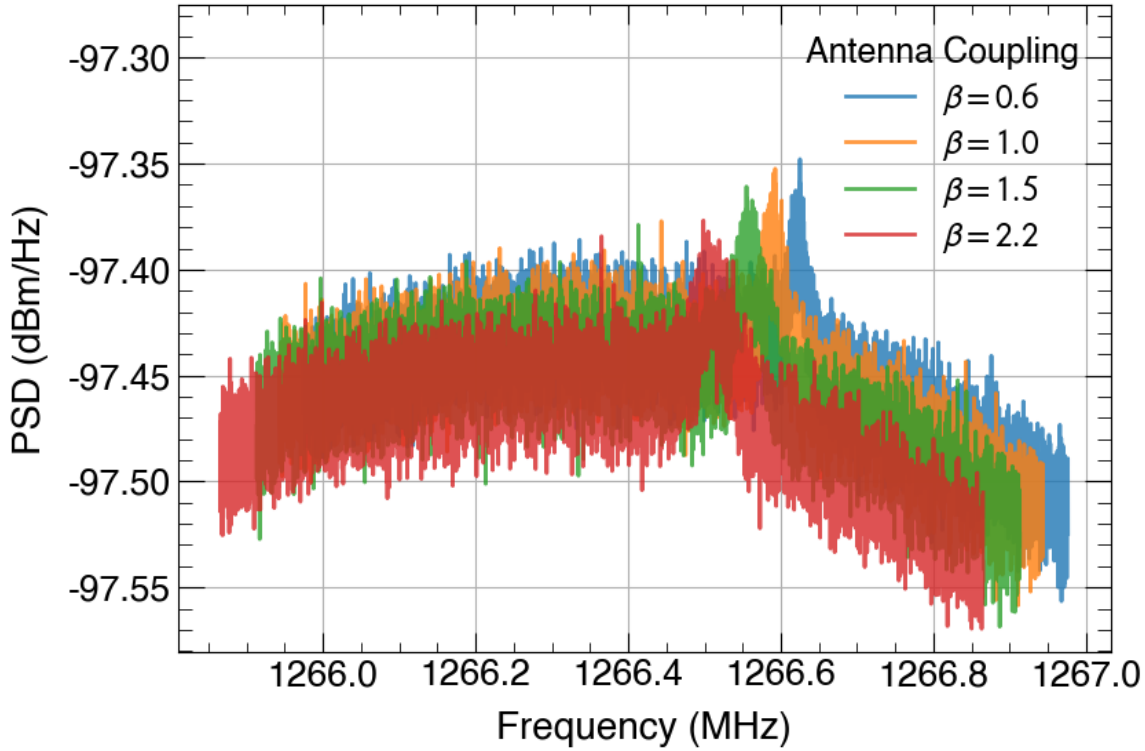
Run 1D

Hot Rod

- A simple hypothesis: poor thermalization leaves the tuning rod hotter than the cavity walls.
- To test for excess cavity noise, we recorded JPA-off spectra at several antenna couplings.

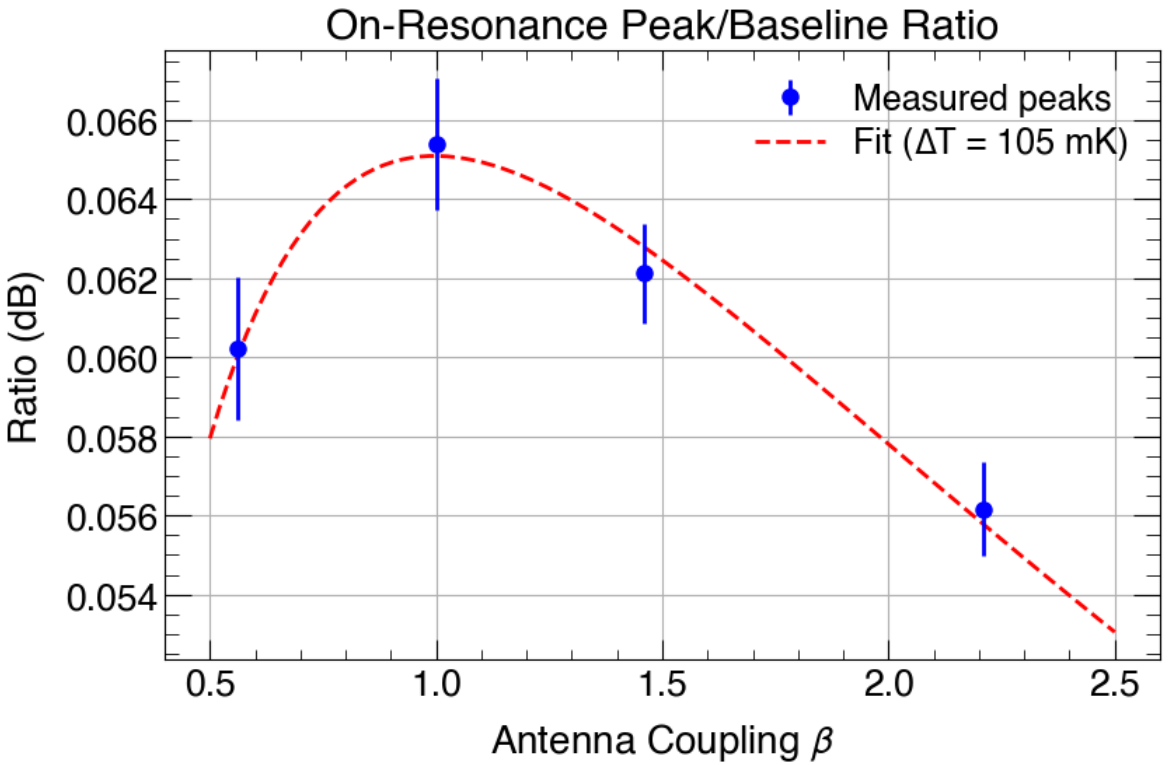


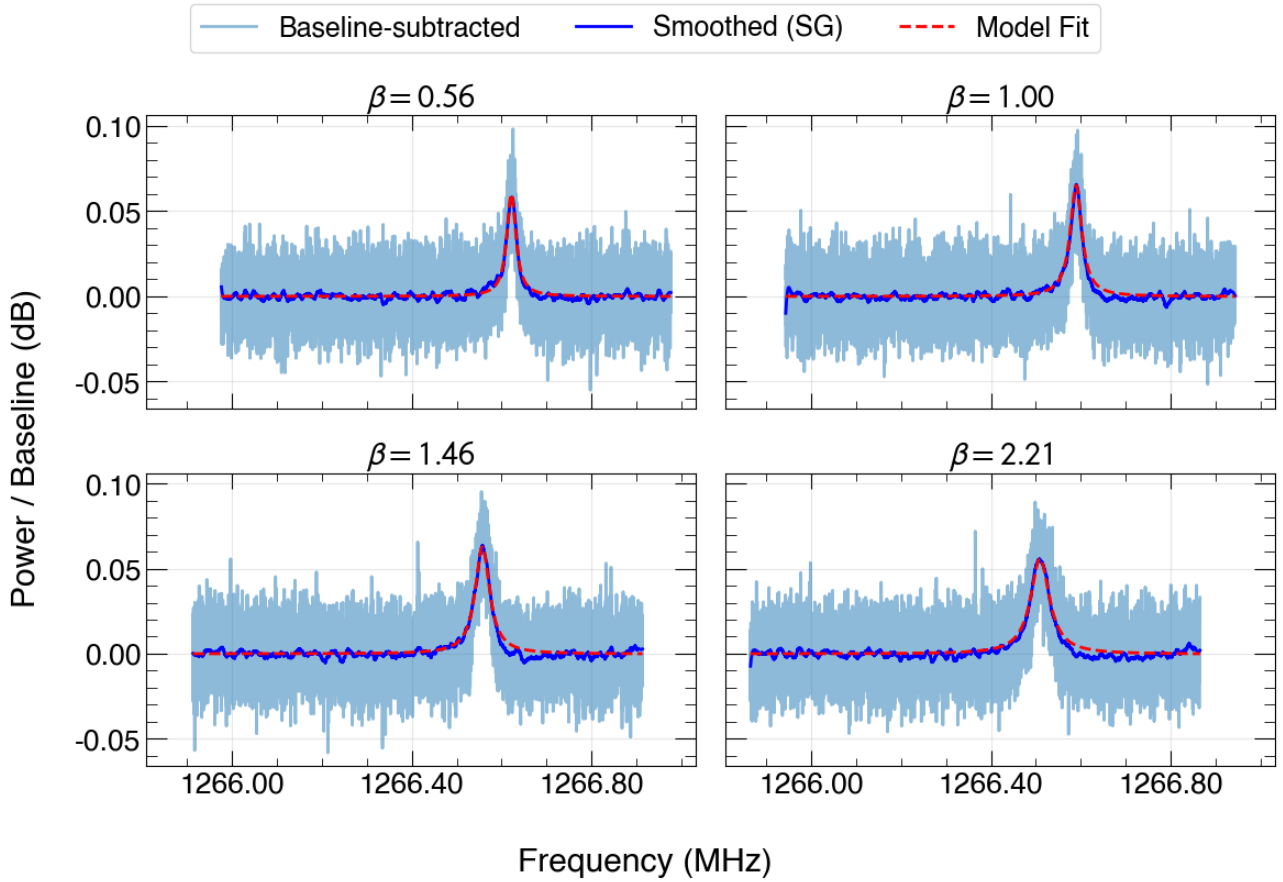
Run 1D



Hot Rod

- The fit suggests an effective cavity-mode temperature ~0.1 K above the sensor reading.





Fit model uses:

$$S(\omega) \sim R(\omega)\, k_B T_{\text{in}} + \big(1 - R(\omega)\big)\, k_B (T_{\text{cav}} + \Delta T)$$

sensor

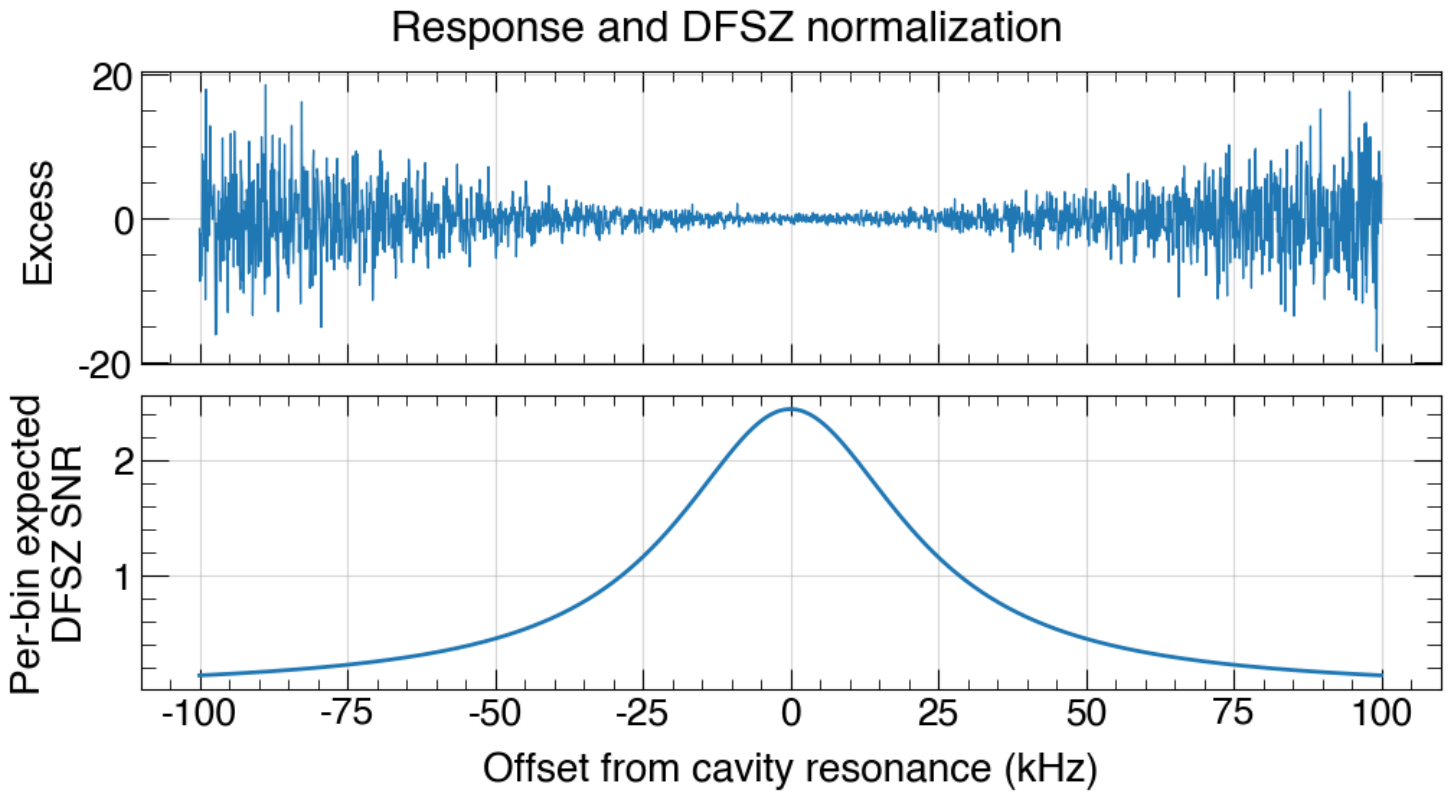
Analysis Pipeline

DQC-passed raw spectra → Baseline removal → **Response and DFSZ normalization** → Axion lineshape fit → Grand spectrum → Candidate rescan → Discovery or exclusion

P_{raw} $\quad x = \frac{P_{\mathrm{raw}}}{B} - 1$ $\quad u = \frac{x\, k_B T_{\mathrm{sys}} \Delta\nu}{P^{\mathrm{DFSZ}}}$

- Normalize the fractional excess by the expected DFSZ signal power, including the cavity response.

$$u = \frac{x\, k_B T_{\mathrm{sys}} \Delta\nu}{P^{\mathrm{DFSZ}}}$$



Analysis Pipeline

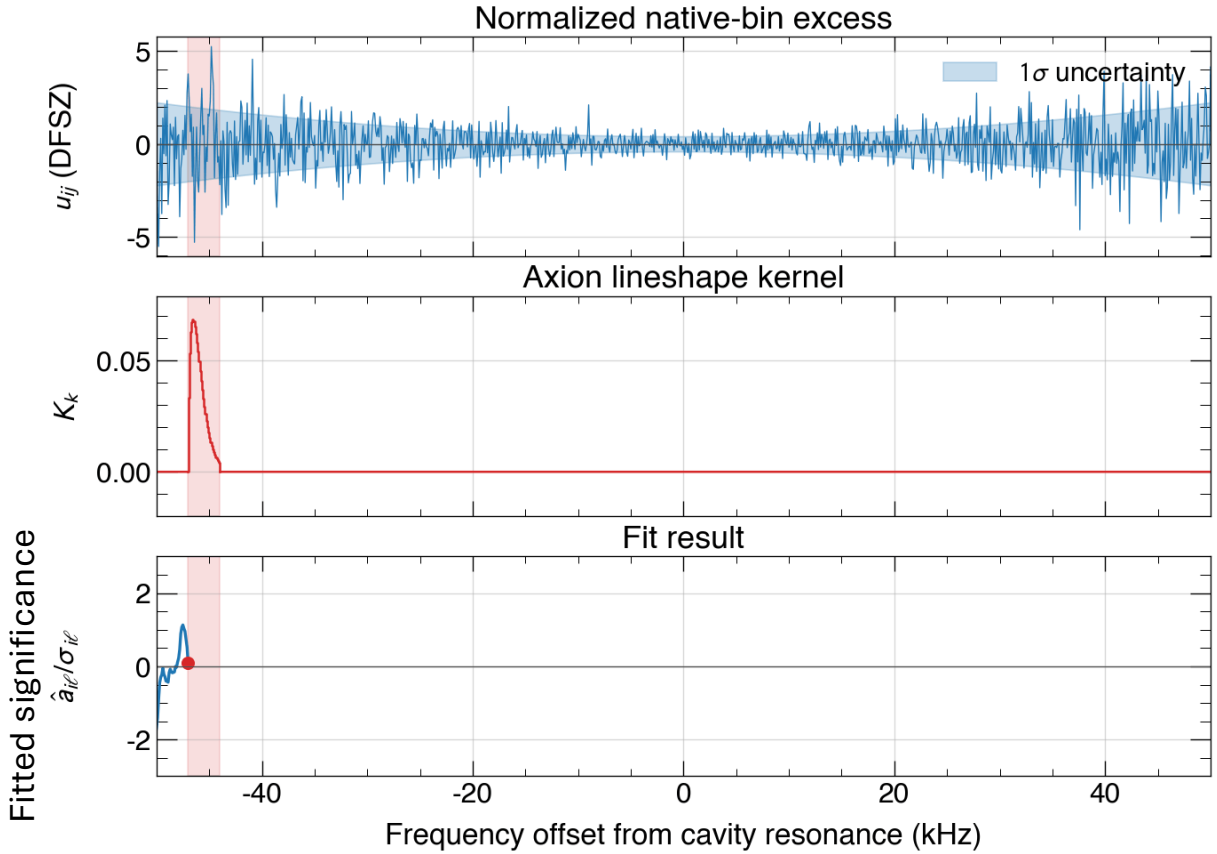
DQC-passed raw spectra → Baseline removal → Response and DFSZ normalization → **Axion lineshape fit** → Grand spectrum → Candidate rescan → Discovery or exclusion

P_{raw} $\quad x = \frac{P_{\mathrm{raw}}}{B} - 1$ $\quad u = \frac{x\, k_B T_{\mathrm{sys}} \Delta\nu}{P^{\mathrm{DFSZ}}}$ $\quad \hat{a} = \frac{\sum Ku/\sigma_u^2}{\sum K^2/\sigma_u^2}$

- A roughly 1 kHz halo signal spans about ten 100 Hz bins.

- Apply the standard halo model lineshape kernel (K) as a matched-template fit

$$\hat{a} = \frac{\sum Ku/\sigma_u^2}{\sum K^2/\sigma_u^2}$$



Analysis Pipeline

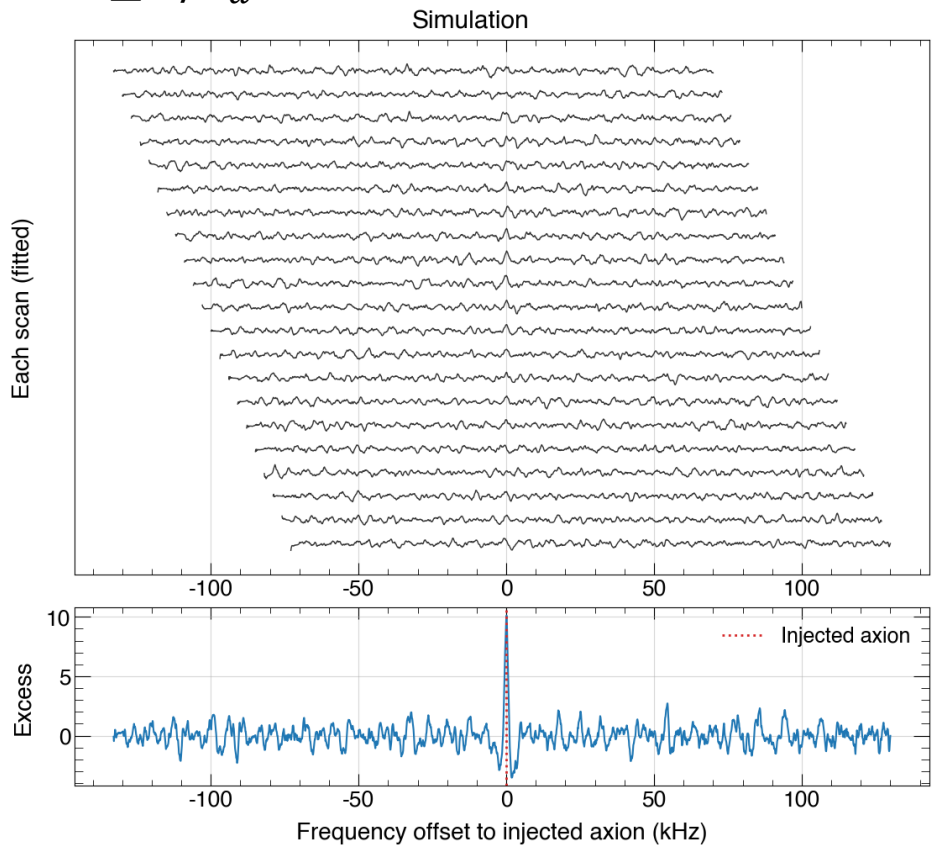
DQC-passed raw spectra → Baseline removal → Response and DFSZ normalization → Axion lineshape fit → **Grand spectrum** → Candidate rescan → Discovery or exclusion

P_{raw} $\quad x = \frac{P_{\mathrm{raw}}}{B} - 1$ $\quad u = \frac{x\, k_B T_{\mathrm{sys}} \Delta\nu}{P^{\mathrm{DFSZ}}}$ $\quad \hat{a} = \frac{\sum Ku/\sigma_u^2}{\sum K^2/\sigma_u^2}$ $\quad \frac{\sum \hat{a}/\sigma_a^2}{\sum 1/\sigma_a^2}$

- Combine overlapping fitted spectra at each physical frequency using inverse-variance weights:

$$\frac{\sum \hat{a}/\sigma_a^2}{\sum 1/\sigma_a^2}$$

- We search the grand spectrum for significant excesses.



Analysis Pipeline

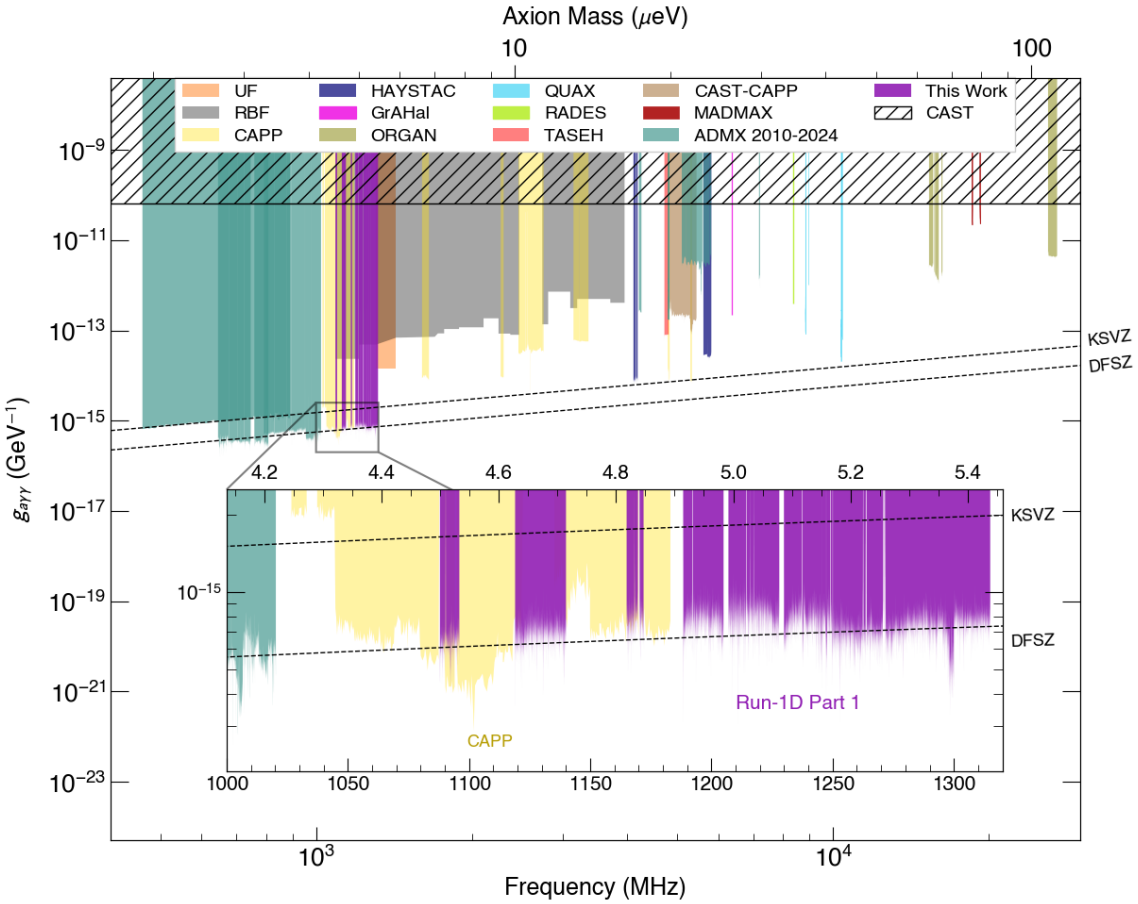


- Rescan targets include excess-power candidates and frequencies with insufficient sensitivity.
  - Most of the time, large excess candidates are statistical flukes.
  - Rescan (take more data) around candidates.
- Persistent excesses receive dedicated follow-up checks. It can be
  - Blind synthetic axion injection (SAG).
  - Ambient RF interference (RFI).
  - **Or axion!**
- Test whether the excess follows the expected axion response.
  - Reduce $B \rightarrow$ axion power $\propto B^2$.
  - Change cavity mode to $TM_{011} \rightarrow$ form factor is near-zero.
  - Identify or remove source of RFI.
  - SAG turned off.

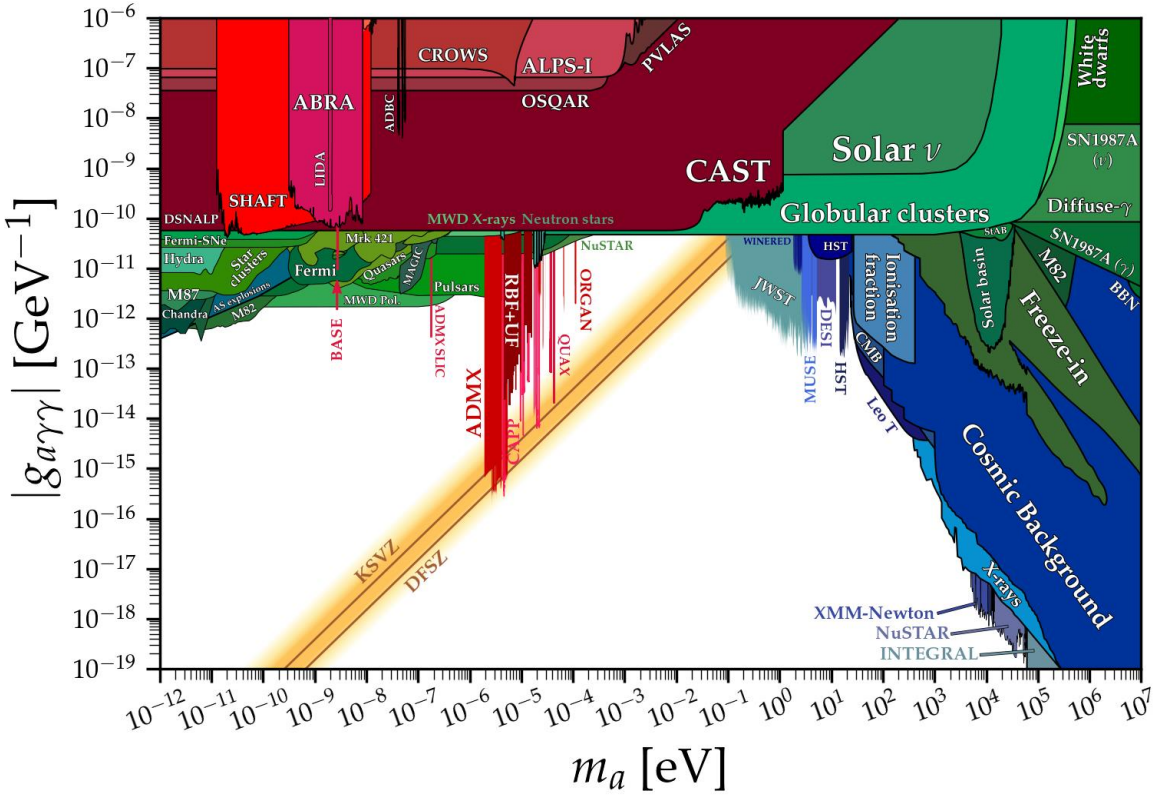
Analysis Pipeline

DQC-passed raw spectra → Baseline removal → Response and DFSZ normalization → Axion lineshape fit → Grand spectrum → Candidate rescan → Discovery or exclusion

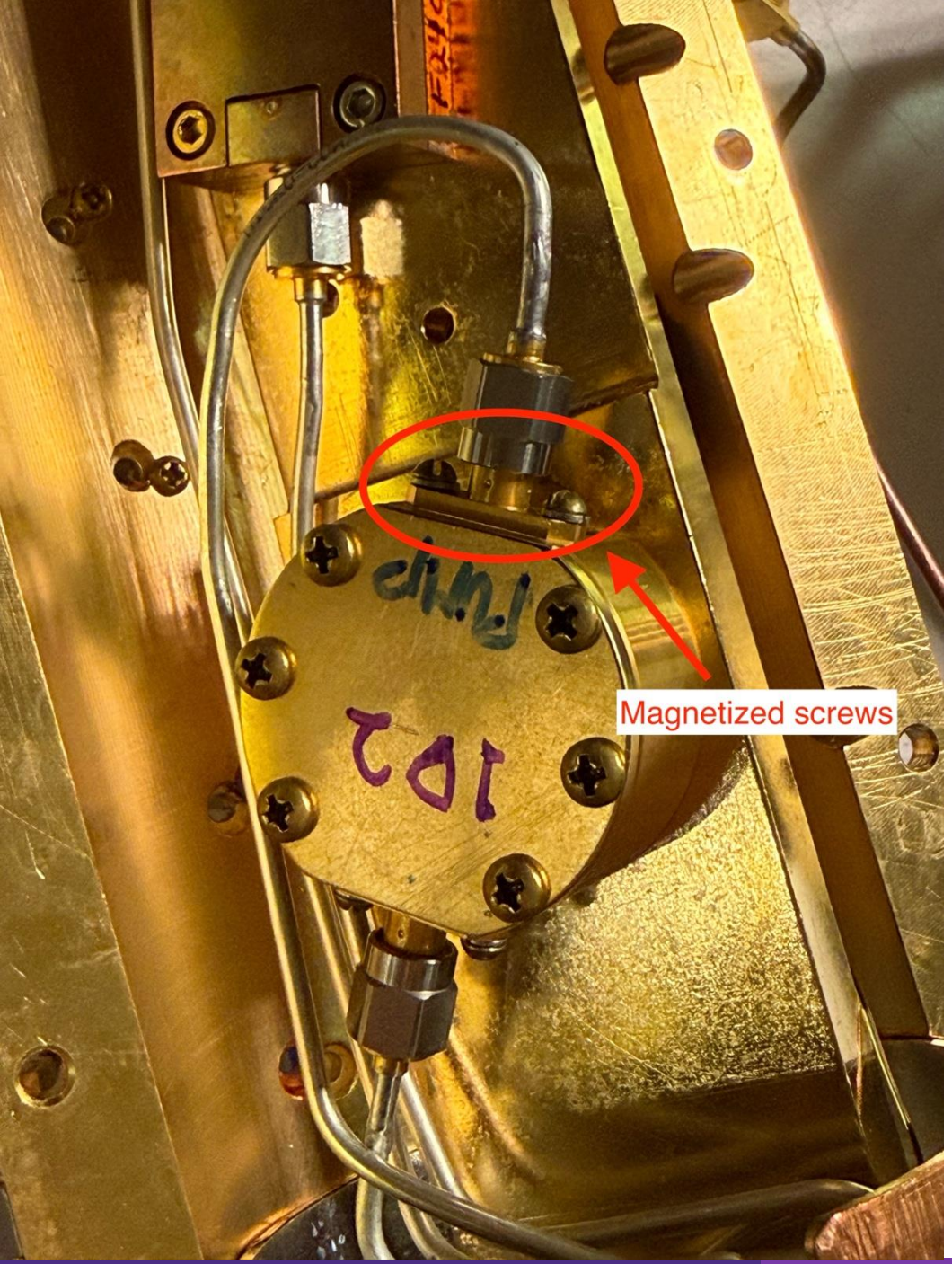
- Assume a local axion density 0.45 GeV/cm^3.
- Set a 90% credible upper limit with a flat prior in nonnegative signal power.

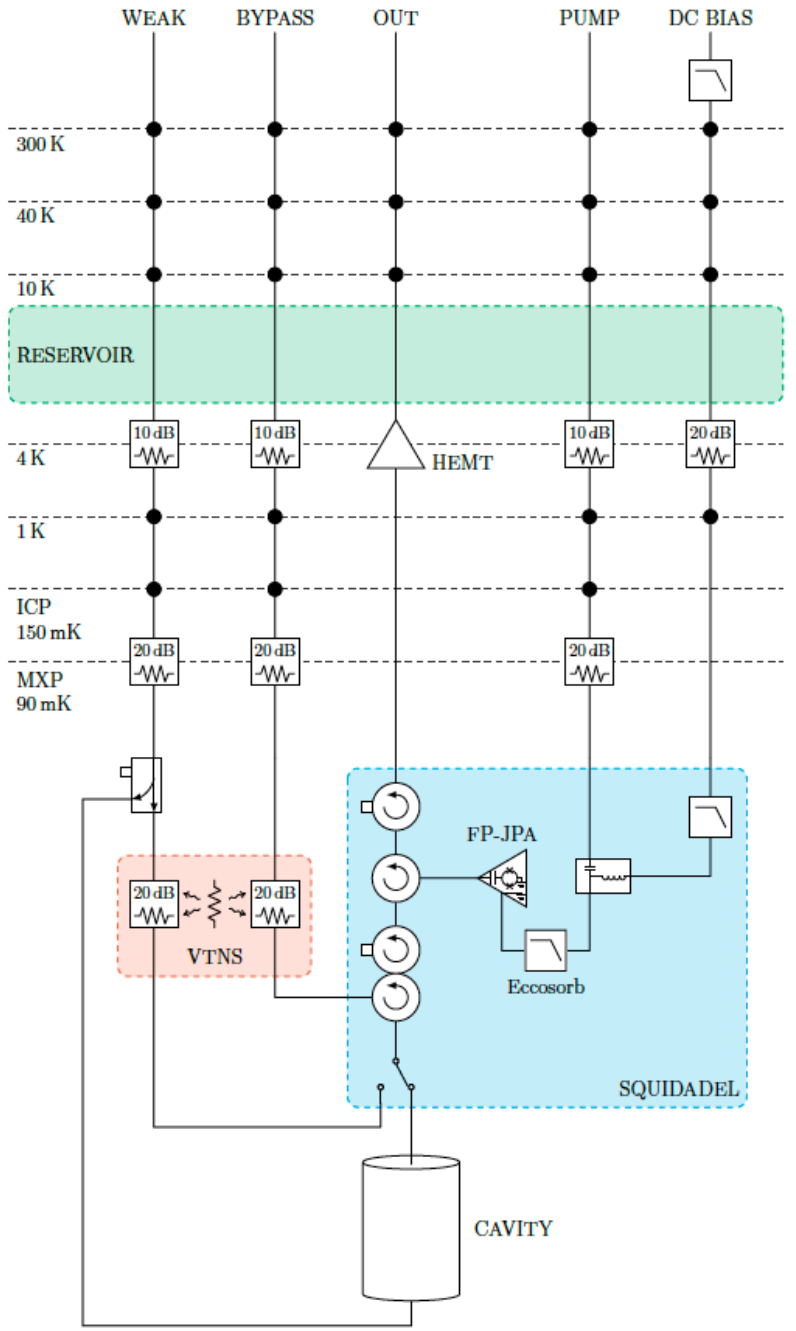


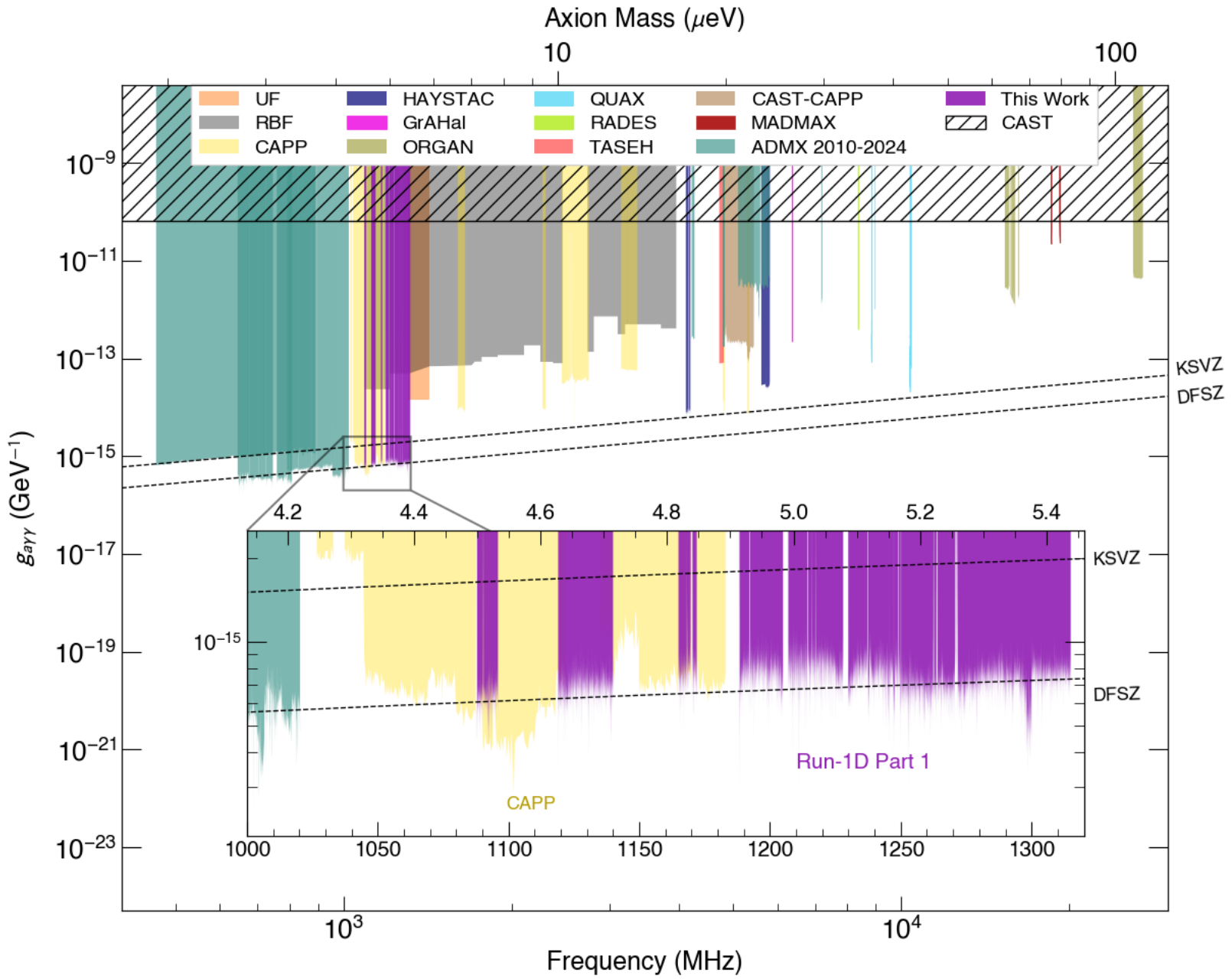
Published Run-1D Part 1 result, PRL **135**, 191001 (2025)

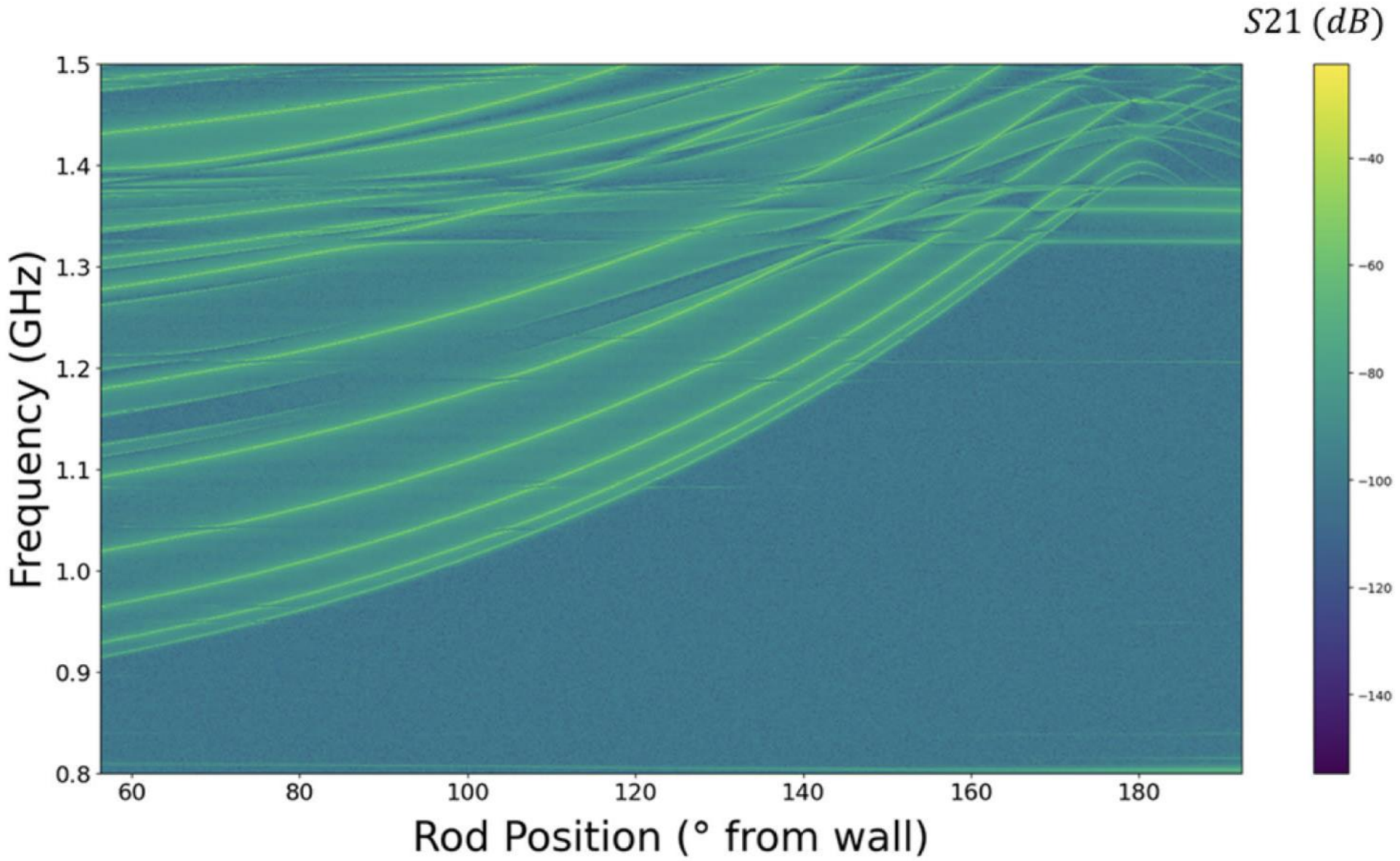


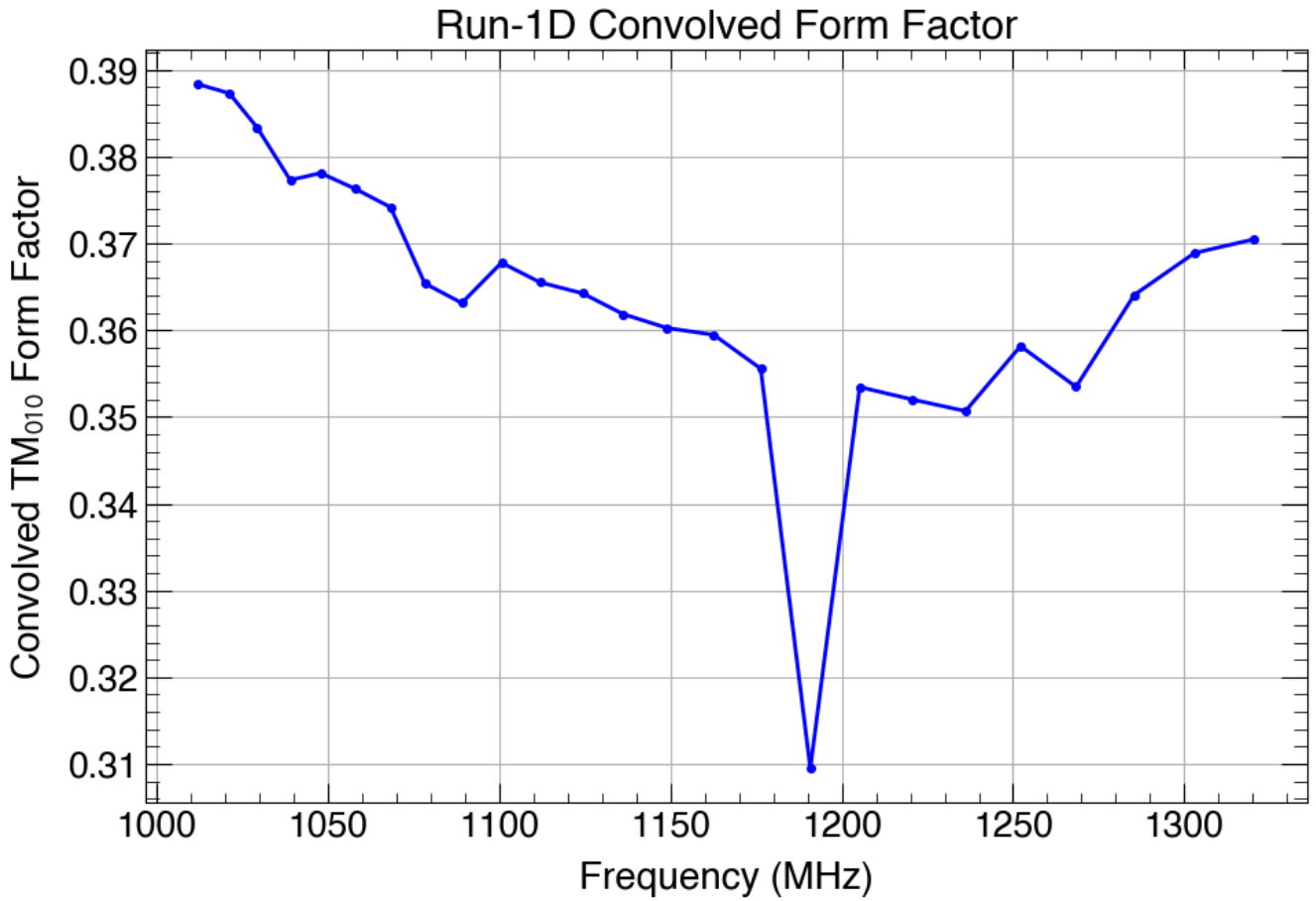
Adapted from 10.5281/zenodo.3932430 by C. O'Hare


Magnetized screws


WEAK
BYPASS
OUT
PUMP
DC BIAS
300 K
40 K
10 K
RESERVOIR
10 dB
10 dB
HEMT
10 dB
20 dB
4 K
1 K
ICP
150 mK
20 dB
20 dB
20 dB
MXP
90 mK
FP-JPA
20 dB
20 dB
VTNS
Eccosorb
SQUIDADEL
CAVITY

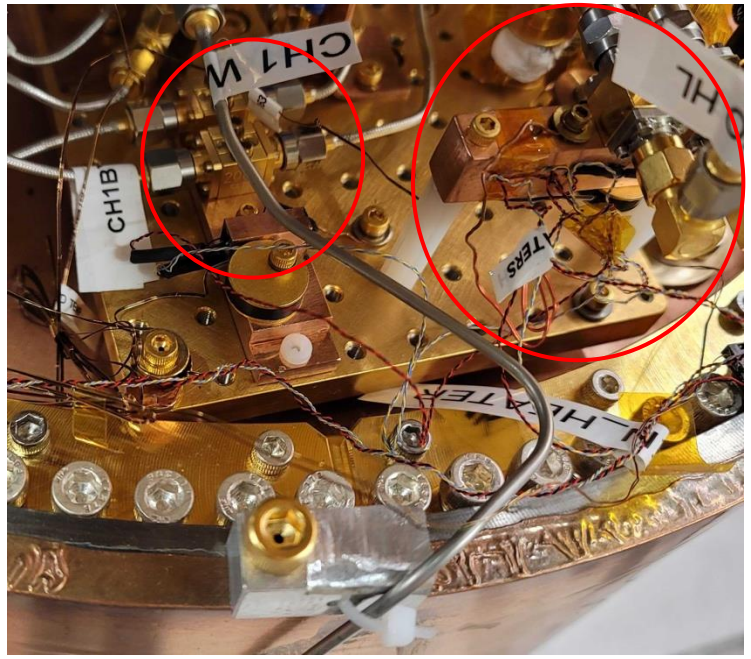

Axion Mass (μeV)
10
100
UF
RBF
CAPP
HAYSTAC
GrAHal
ORGAN
QUAX
RADES
TASEH
CAST-CAPP
MADMAX
ADMX 2010-2024
This Work
CAST
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
10^{-21}
10^{-23}
$g_{a\gamma\gamma}$ (GeV^{-1})
KSVZ
DFSZ
4.2
4.4
4.6
4.8
5.0
5.2
5.4
10^{-15}
KSVZ
DFSZ
Run-1D Part 1
CAPP
1000
1050
1100
1150
1200
1250
1300
10^3
10^4
Frequency (MHz)


$S21\ (dB)$
Frequency (GHz)
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
60
80
100
120
140
160
180
Rod Position (° from wall)
−40
−60
−80
−100
−120
−140


Run-1D Convolved Form Factor
Convolved TM_{010} Form Factor
0.39
0.38
0.37
0.36
0.35
0.34
0.33
0.32
0.31
1000
1050
1100
1150
1200
1250
1300
Frequency (MHz)

System Noise Calibration

mK attenuator Hot load



1. Hot load: connected by the RF switch.
2. mK attenuator (new in Part 2):
   no switch needed. The concept worked!

