Experimental Plan and Execution for Axion Haloscope Detection at 8.8μeV

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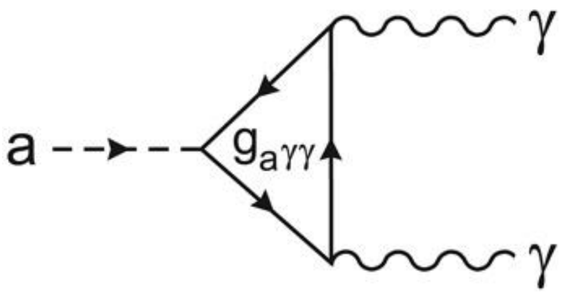
Content in collaboration with: Prof. Chang Yuan-Hann and the TASEH team

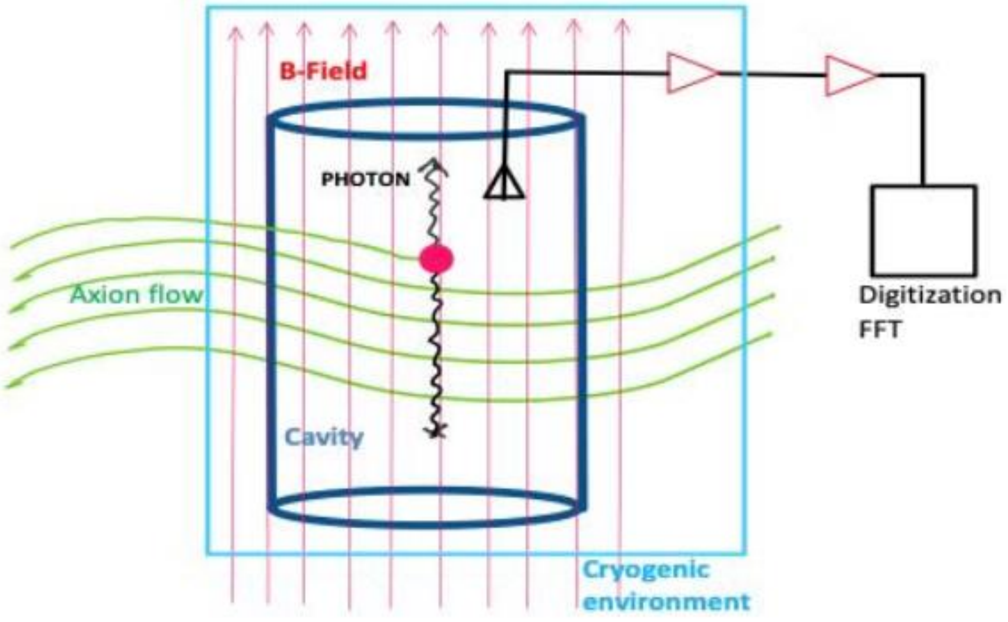
How can we detect Axion?



- Axions will convert to photons in a magnetic field.

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

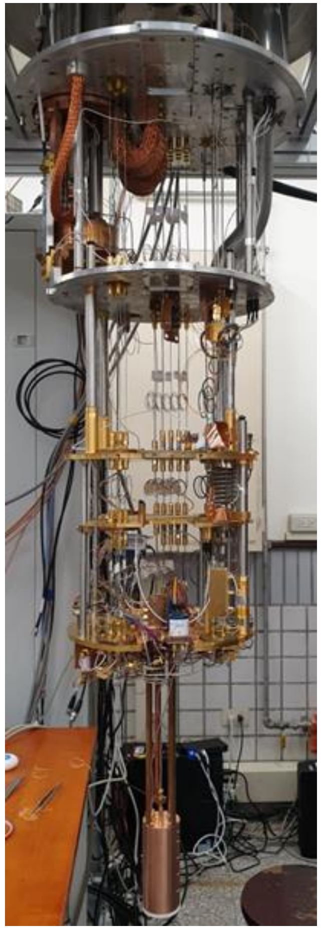
$$P_{a\to\gamma} = \eta g_{a\gamma\gamma}^2 \left[\frac{\rho_a}{m_a}\right] B^2 V C Q_L$$

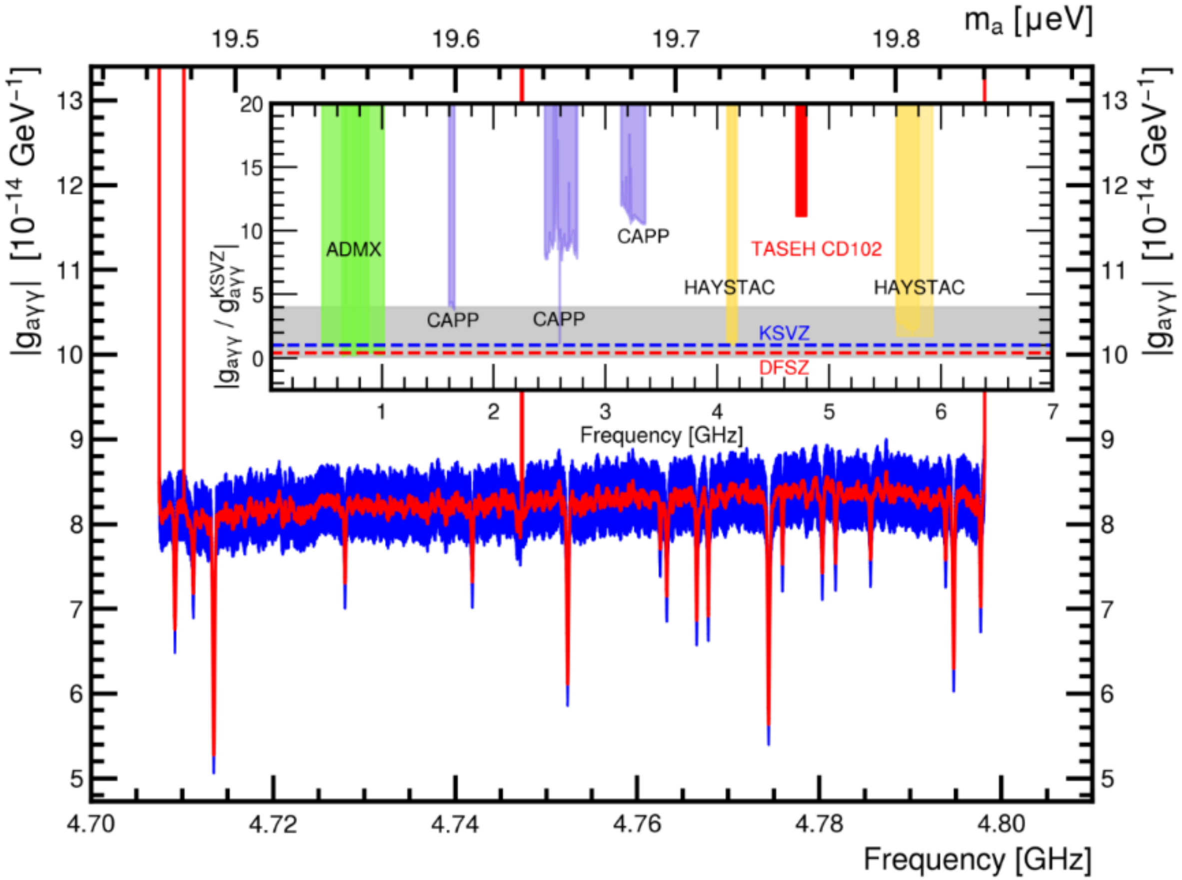


η: The fraction of the converted power transmitted to the readout probe
$g_{a\gamma\gamma}$: The axion-photon coupling constant
ρ_a: local dark matter density
m_a: axion mass
B: magnetic field strength
V: cavity volume
C: form factor
Q_L: the cavity loaded quality factor

CD102 Result

A search excluded $|g_{a\gamma\gamma}| \gtrsim 8.2\times10^{-14}$ GeV^{-1}, a factor of 11 above KSVZ model, in the m_a range 19.47 – 19.84 μeV in 2022.





Chang, Hsin, et al. "First results from the Taiwan axion search experiment with a haloscope at 19.6 μeV." *Physical Review Letters* 129.11 (2022): 111802.

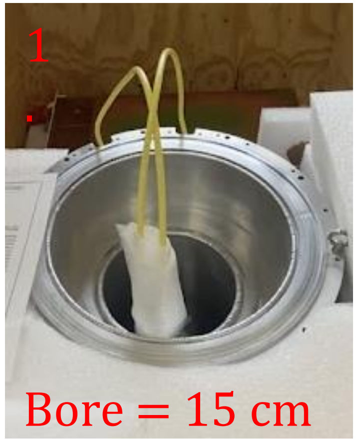
Overview

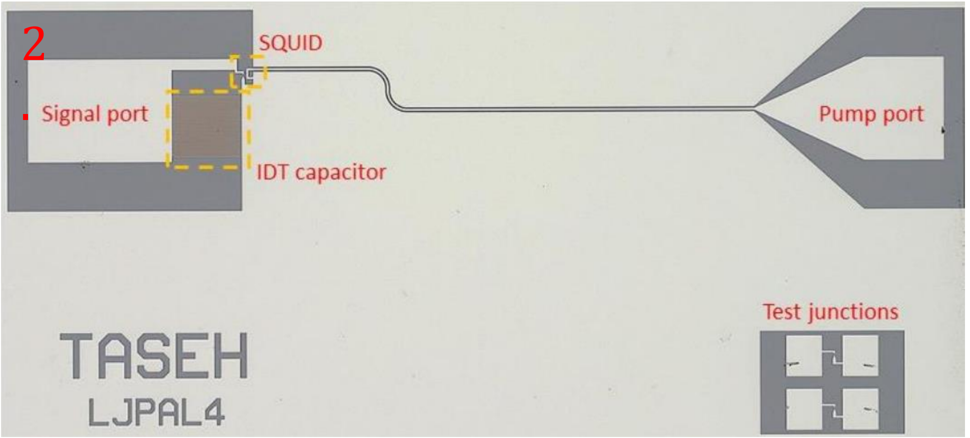
Target:

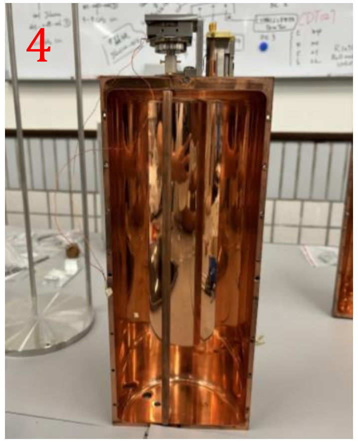
An axion haloscope search the m_a region: 8.48-9.10 μeV (2-2.3 GHz), excluding $|g_{a\gamma\gamma}| \gtrsim 7.5\times10^{-15}$ GeV^{-1} (theoretic value of KSVZ model)

Configuration plan:

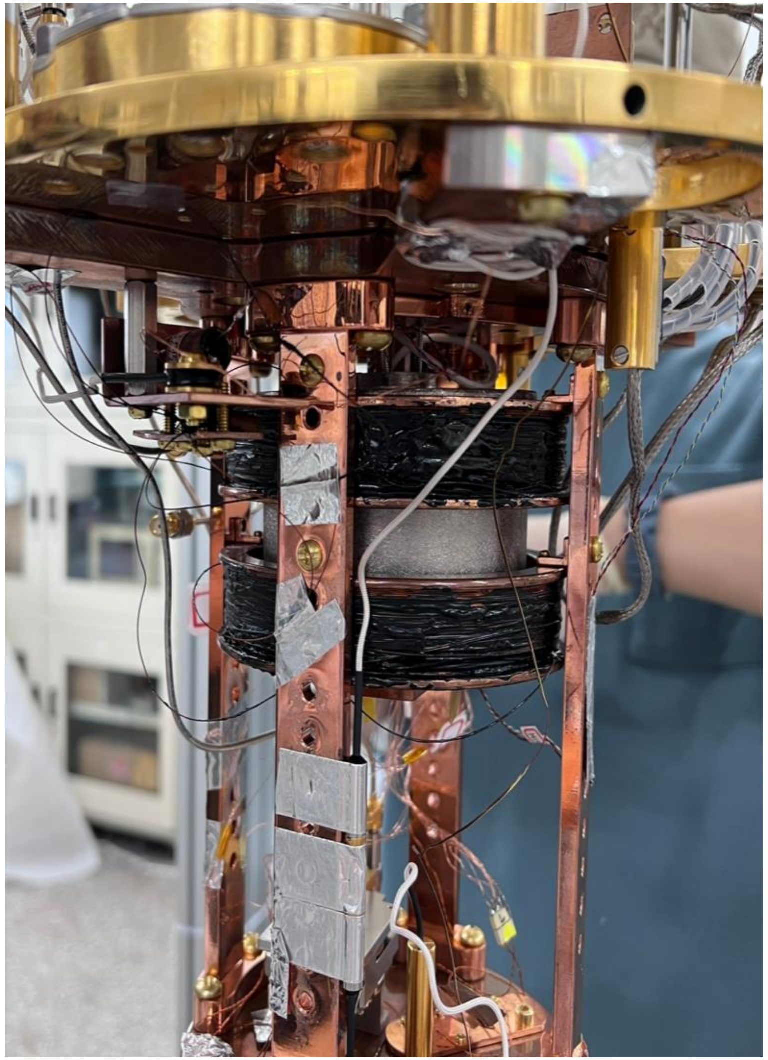
1. Superconducting magnet, providing B = 6 T at the center
2. Josephson parametric amplifier (JPA), providing T_{sys} = 240 mK (two-photon noise)
3. Magnetic shielding, protection the JPA from the surrounding magnetic field.
4. Tunable cylindrical 2-2.3 GHz cavity, with V = 4 L, C = 0.46, and Q = 8×10^3
5. Cavity radiation calibration, a method directly characterizing the detection chain

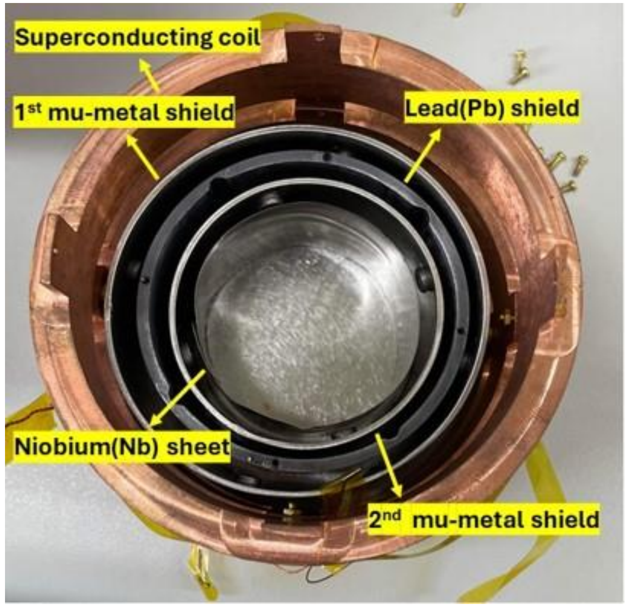


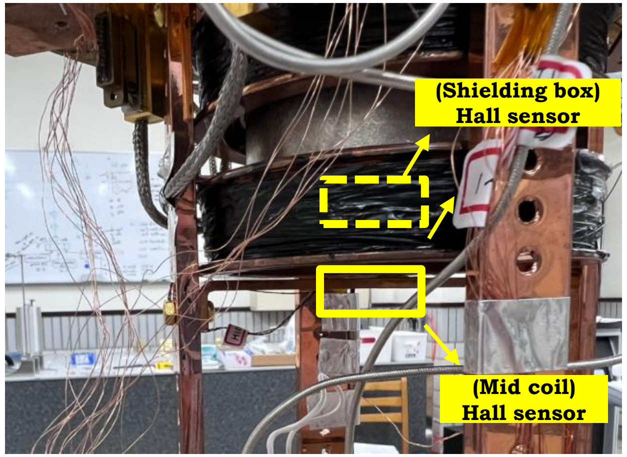


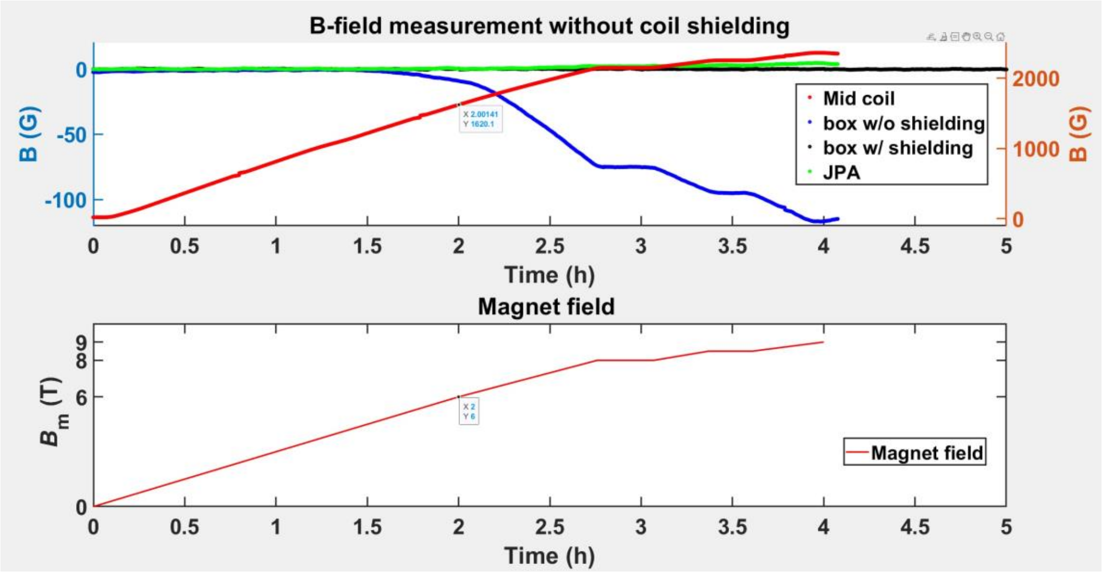


Magnetic Shielding



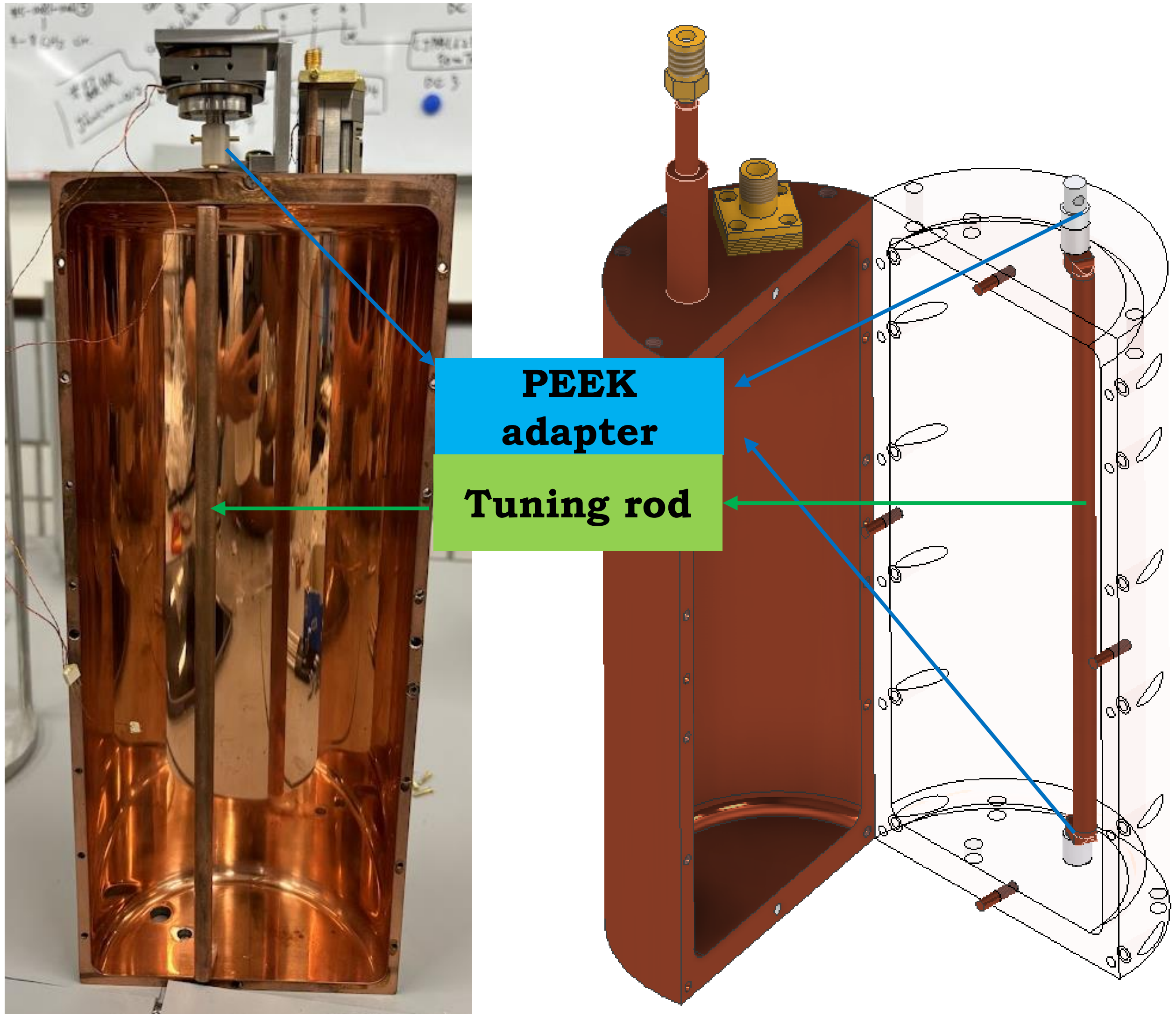






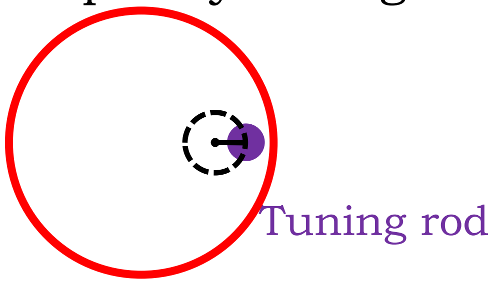
- The superconducting coils and five-layer magnetic shield protects the JPA from ~ 1600 G magnetic field is confirmed by the readings from the two Hall sensors.
- We avoid ramping up to 9 T to further prevent magnetic field penetration inside the shielding.

Cylindrical Cavity



Copper-coated cavity

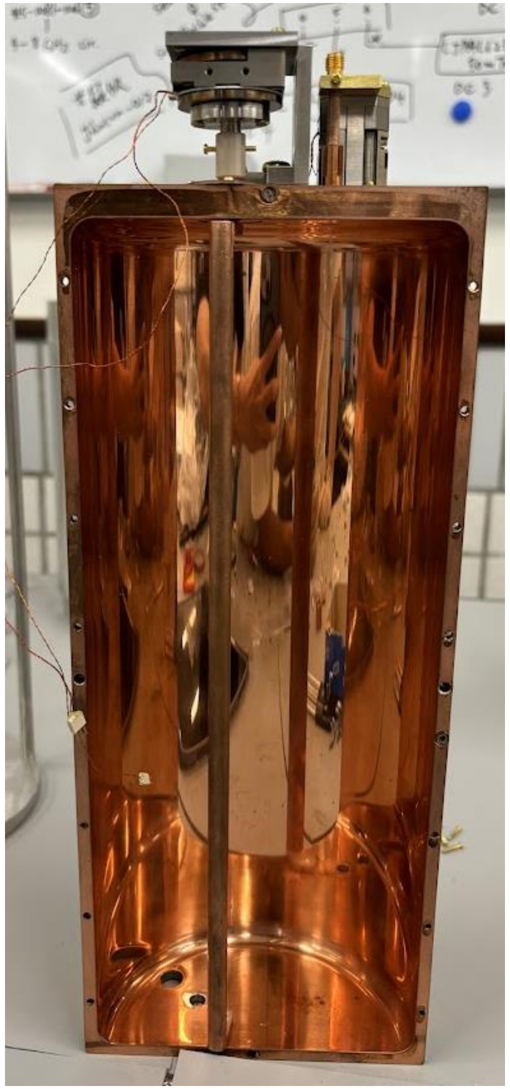
Frequency tuning mechanism

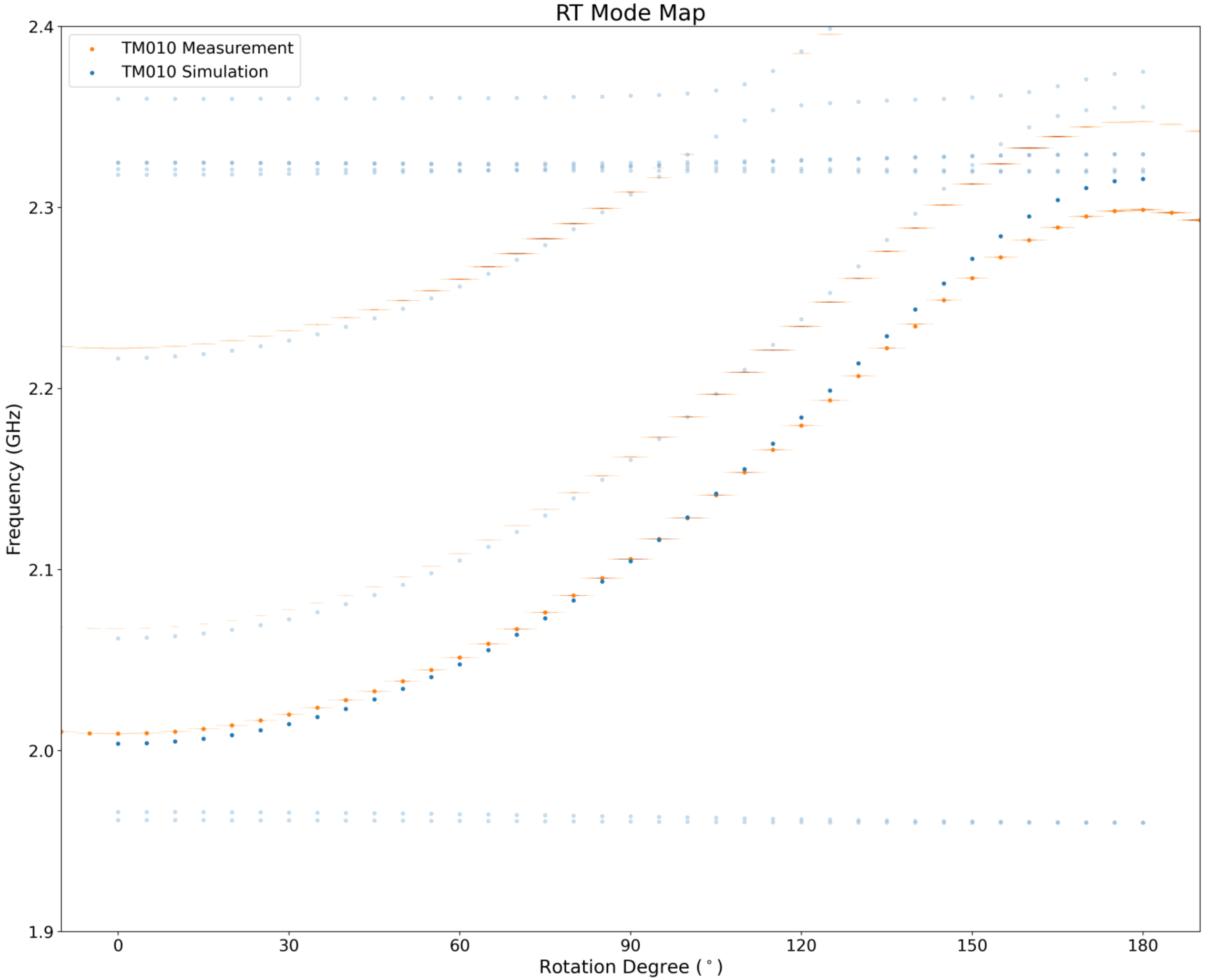


$$f_{nml} = \frac{c}{2\pi\sqrt{\epsilon_r\mu_r}}\sqrt{(\frac{p_{nm}}{r})^2+(\frac{l\pi}{h})^2}$$

- $f_r = 2.0 - 2.3$ GHz
- D = 128 mm : (diameter)
- L = 320 mm : (height)
- $V \sim 4$ L
- $C \sim 0.46$
- $Q_L \sim 8000$

Cylindrical Cavity





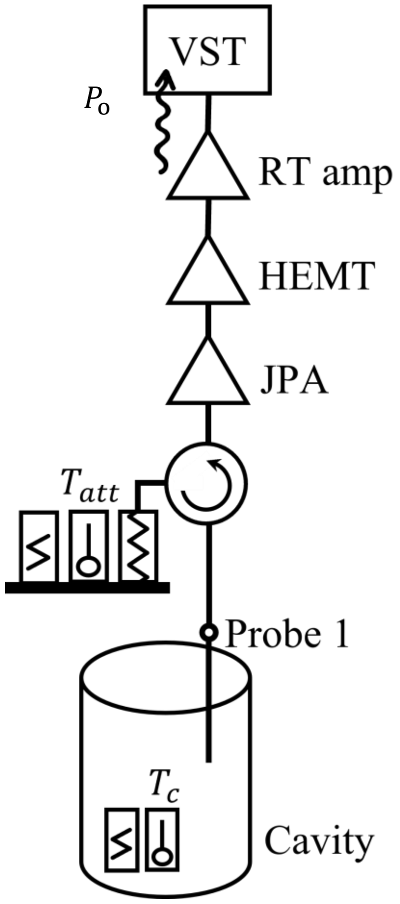
Cavity radiation calibration

- Calibration is crucial for finding gain of the output signal in the detection chain and the system noise of the system.

$$P_o = G k_B \Delta f\left(|S_{11}|^2 \tilde{T}_{att} + |S_{10}|^2 \tilde{T}_c + \tilde{T}_a\right), \begin{cases} S_{11}(f) = \frac{(\kappa_0-\kappa_1)/2\pi+2i(f-f_0)}{(\kappa_0+\kappa_1)/2\pi+2i(f-f_0)} \\ S_{10}(f) = \frac{2\sqrt{\kappa_1\kappa_0}/2\pi}{(\kappa_0+\kappa_1)/2\pi+2i(f-f_0)} \end{cases}.$$

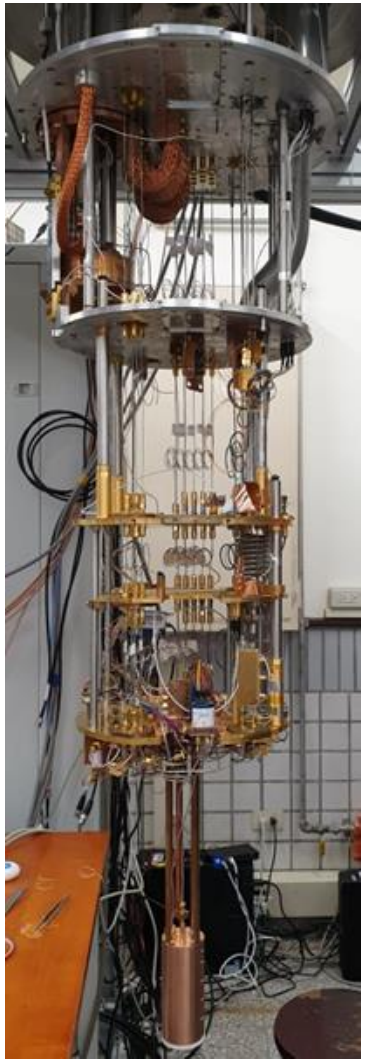
- We have a known radiation power from cavity as our calibration source, to precisely characterize our detection chain.

- This calibration method has been successfully carried out in a 4 GHz cavity with an expected result.

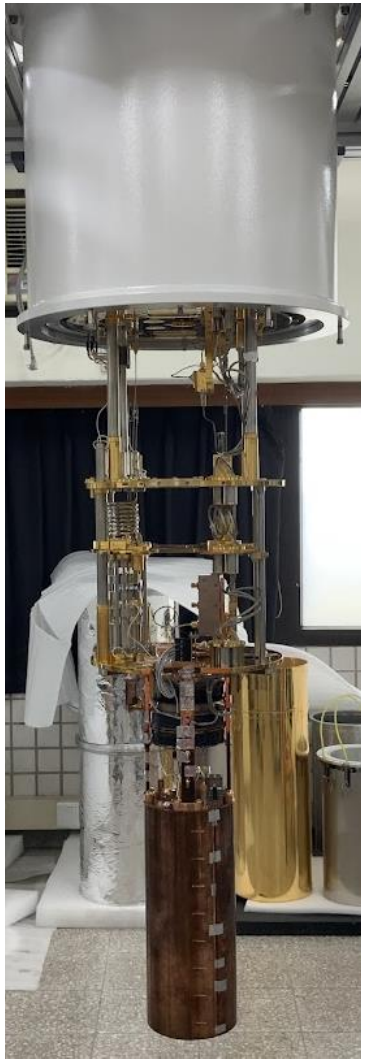


Expectation

CD102



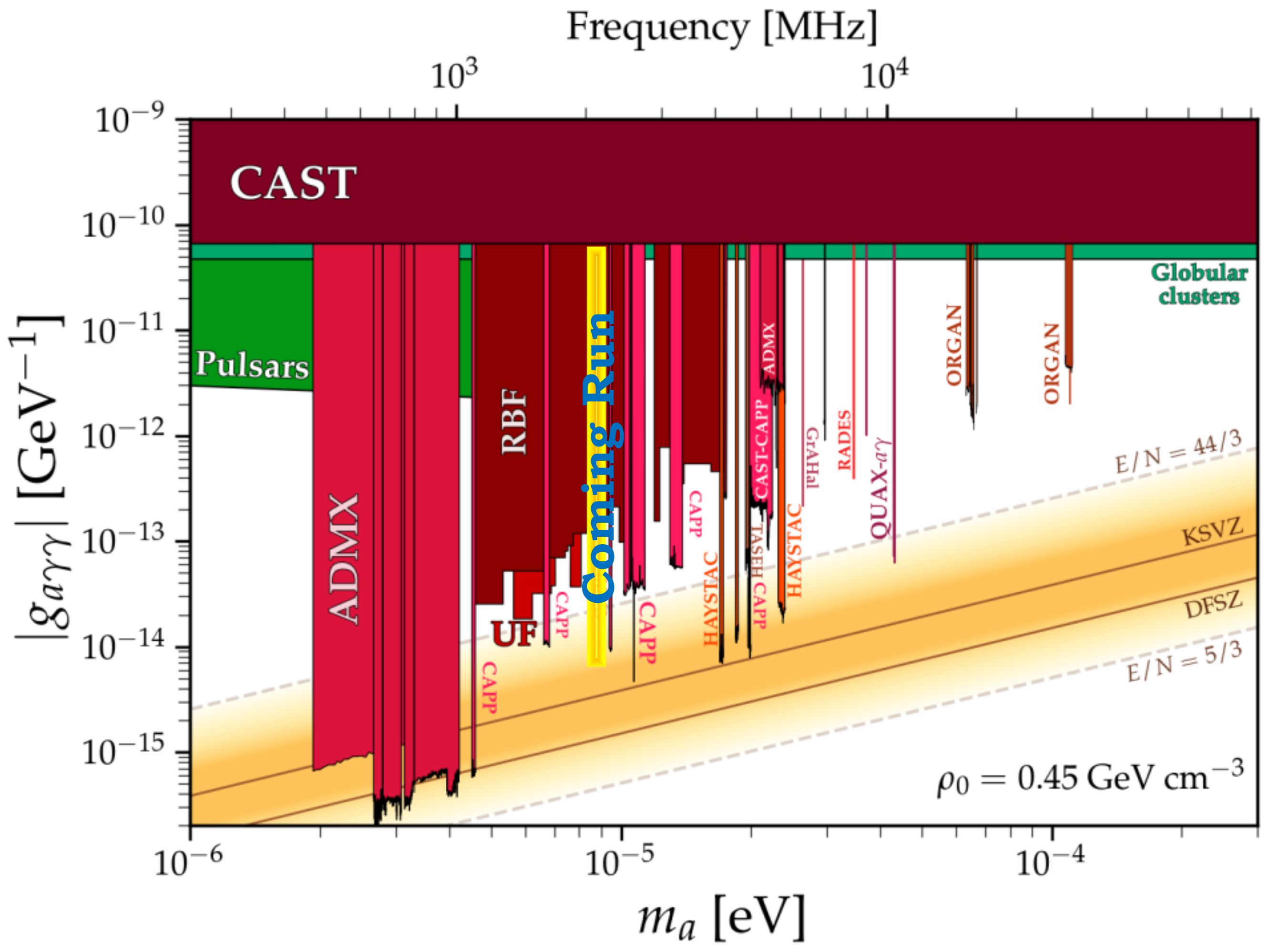
Coming run



$$P_{a\to\gamma} = \eta g_{a\gamma\gamma}^2 \left[\frac{\rho_a}{m_a}\right] B^2 V C Q_L,\ \ g_{a\gamma\gamma} = \left(\frac{g_\gamma \alpha}{\pi \Lambda^2}\right) m_a$$

Parameter	CD102	Coming run
T_{sys} (mK)	2300	240
η	0.69	0.67
m_a (μeV)/ f_c (GHz)	19.47 – 19.84/ 4.71 – 4.80	8.48 – 9.10/ 2 – 2.3
B (T)	7.8	6
V (L)	0.23	4
C	0.67	0.46
Q_L	2.0×10^4	8×10^3
$\lvert g_{a\gamma\gamma}/g_{a\gamma\gamma}^{KSVZ}\rvert$	11	2.7

Expectation

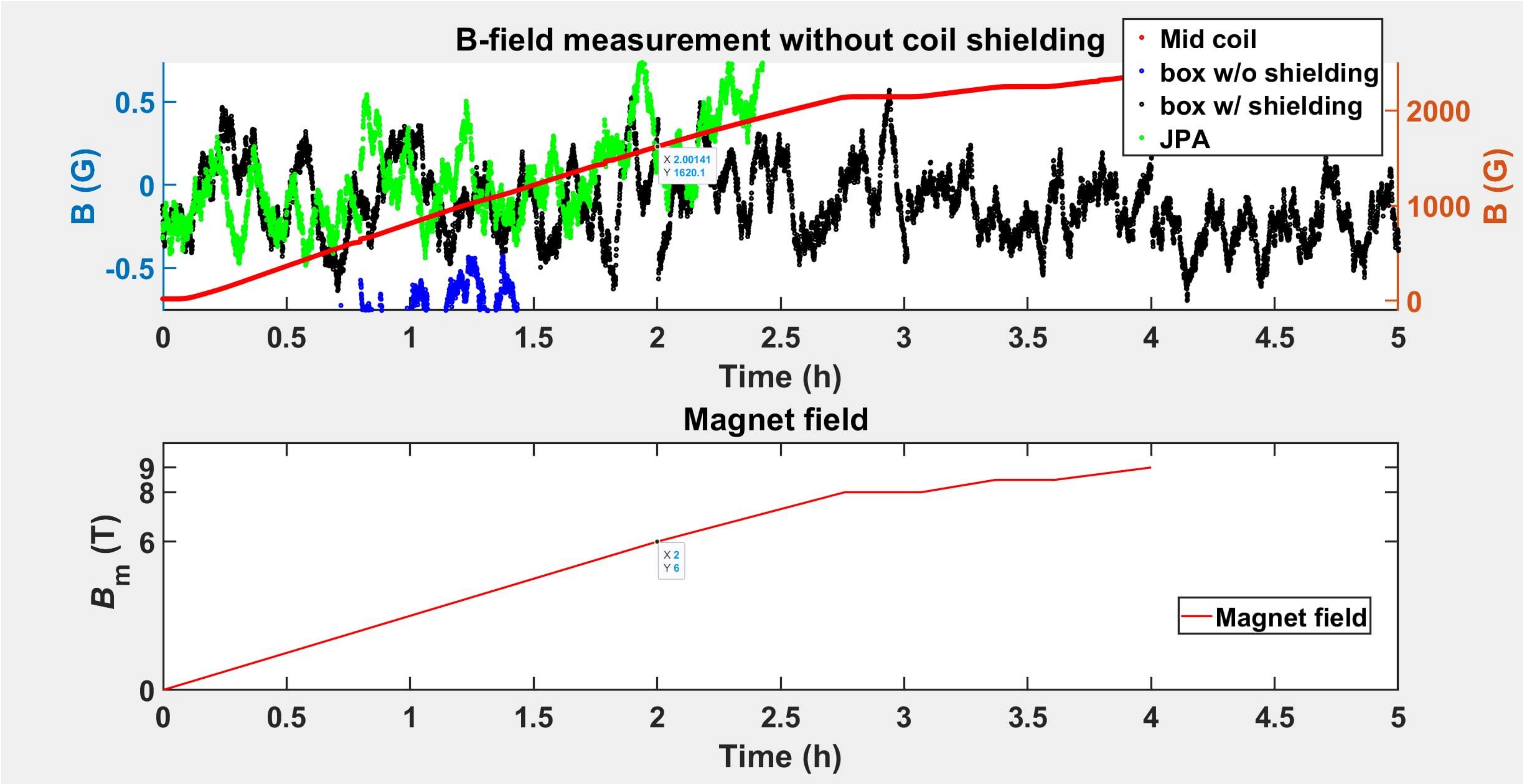


Conclusion

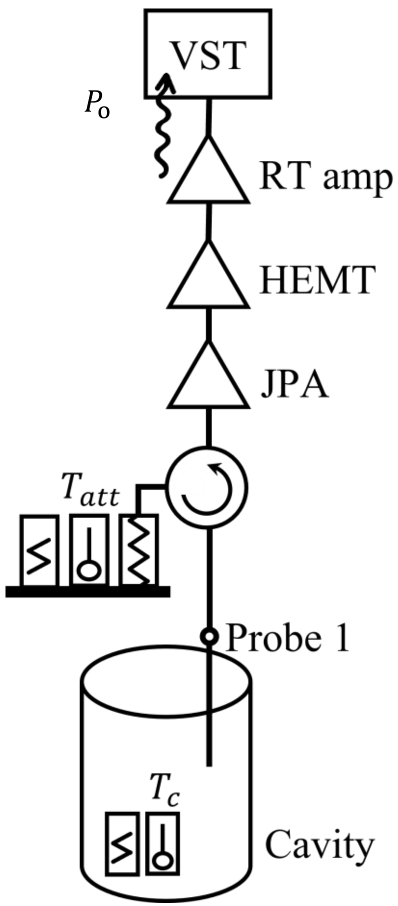
1. Four goals have been achieved for the following run.
   - A JPA reduce the system noise to the level of two-photon noise.
   - The 2GHz cavity works at low temperatures.
   - The shielding ability have been confirmed with Hall sensors.
   - The system noise is accurately determined through cavity radiation calibration.

2. We are ready to proceed with a data taking run this year.

Magnetic Shielding



Cavity radiation calibration



- The detection chain for axion haloscope search is the signal path from a cavity to the signal analyzer, where the gain is G and the system noise is given by

$$T_{sys} = \frac{1}{k_B \Delta f} \frac{P_{ave}/G}{\sqrt{N_{ave}}}.$$

- The radiation emitted from an object x is

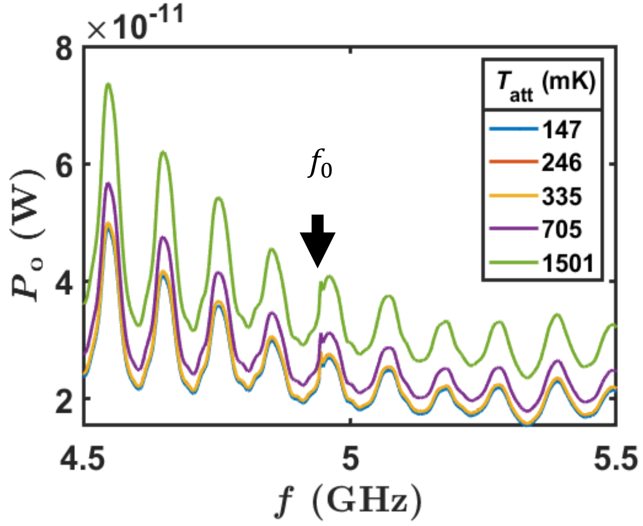
$$\tilde{T}_x = \frac{hf}{k_B}\left(\frac{1}{e^{\frac{hf}{k_B T_x}}-1} + \frac{1}{2}\right).$$

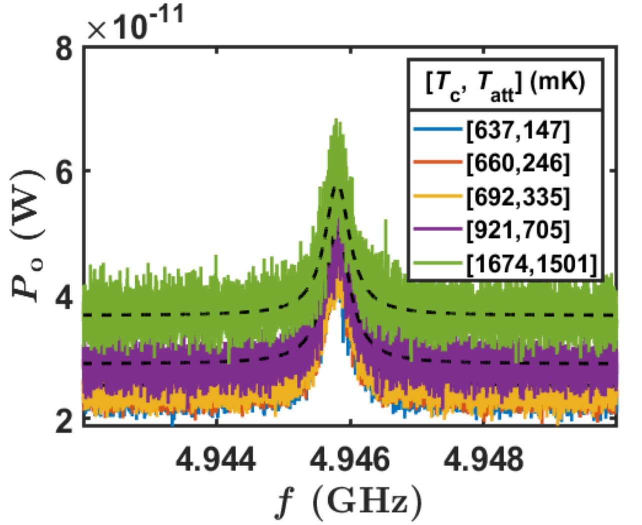
- The output power of the detection chain is

$$P_o = G k_B \Delta f\left(|S_{11}|^2 \tilde{T}_{att} + |S_{10}|^2 \tilde{T}_c + \tilde{T}_a\right),$$

$$\begin{cases} S_{11}(f) = \dfrac{(\kappa_0-\kappa_1)/2\pi + 2i(f-f_0)}{(\kappa_0+\kappa_1)/2\pi + 2i(f-f_0)} \\ S_{10}(f) = \dfrac{2\sqrt{\kappa_1\kappa_0}/2\pi}{(\kappa_0+\kappa_1)/2\pi + 2i(f-f_0)} \end{cases}.$$

- This calibration method has been successfully carried out in a 4 GHz cavity.





Exclusion Plot