Ultra-Low Noise Axion Dark Matter Search Using a Josephson Parametric Amplifier at CAPP

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ABSTRACT

Axions, hypothetical particles associated with the spontaneous breaking of a postulated U(1) symmetry, offer a dynamic solution to the strong CP problem, an important puzzle in the standard model (SM). Axions in the mass range of 1 μeV - 10 meV are considered as favored candidates for dark matter. They have extremely weak interactions with the SM fields, making relevant searches exceptionally difficult. To date, the cavity haloscope has remained the most sensitive approach in this mass range. Relying on the two-photon coupling, it utilizes a frequency-tunable microwave cavity immersed in a strong magnetic field. The Center for Axion and Precision Physics Research recently implemented a flux-driven Josephson parametric amplifier in the receiver chain of an axion haloscope, reducing the system's noise down to 200 mK. We present the results of the axion dark matter search for the mass range of 9.39 - 9.51 μeV. We also discuss a newly developed scanning method that can improve the scan speed by approximately 30%.

SCANNING RATE

- Axion is a dark matter candidate, originally introduced to explain strong CP problem by Peccei-Quinn[1]. Axion can couple to two photons. Using this interaction, one can obtain photon from axion, by applying magnetic field. This photon can be measured **as RF signal.**
- **Axion conversion power[2]:**

$$P_s = \left[g_\gamma^2 \frac{\alpha^2}{\pi^2}\right]\left[\left(\frac{h}{2\pi}\right)^3 c^3 \frac{\rho_a}{\Lambda^4}\right]\left[\omega_0 B_0^2 \frac{V}{\mu_0}\right]\left[\frac{\beta}{1+\beta}\frac{C_{nlm}Q_L}{1+(2\delta\nu/\Delta\nu_c)^2}\right]$$

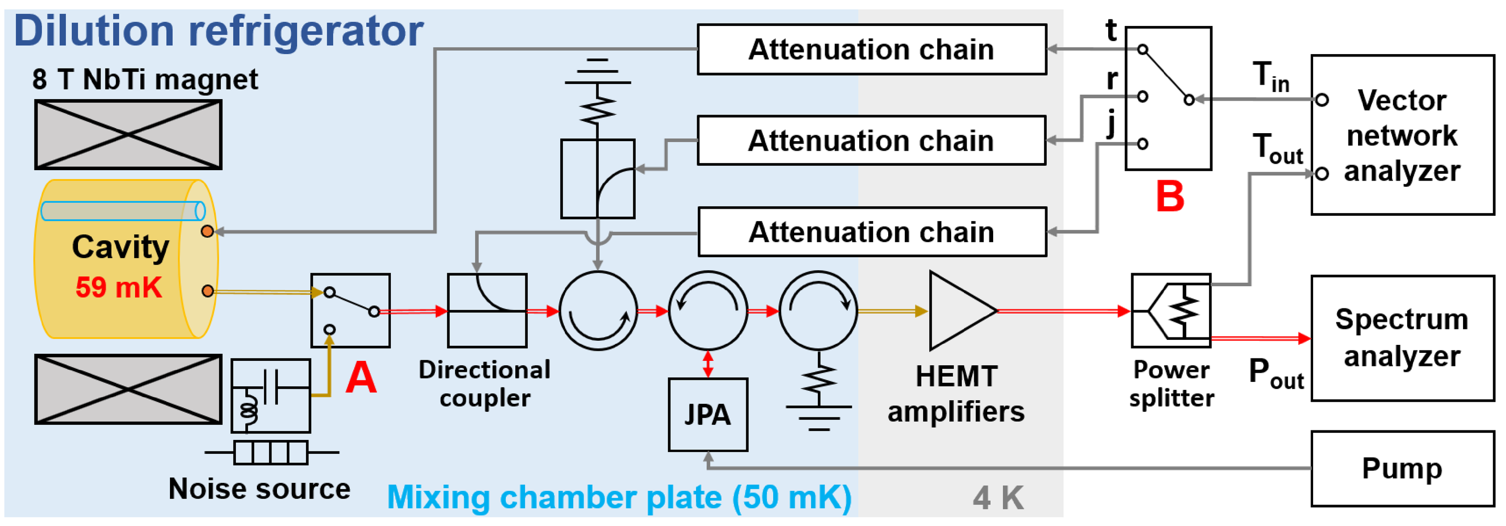
(g_γ = model-dependent parameter)

- **Scanning rate from conversion power:**

$$\frac{d\nu}{dt} \propto \frac{(CV)^2 Q}{T_{sys}^2}$$

To enhance scanning rate → 1. Increase Q, C, V (Cavity) **2. Reduce T_{sys} (Pre-amp.)**

RF CHAIN SETUP

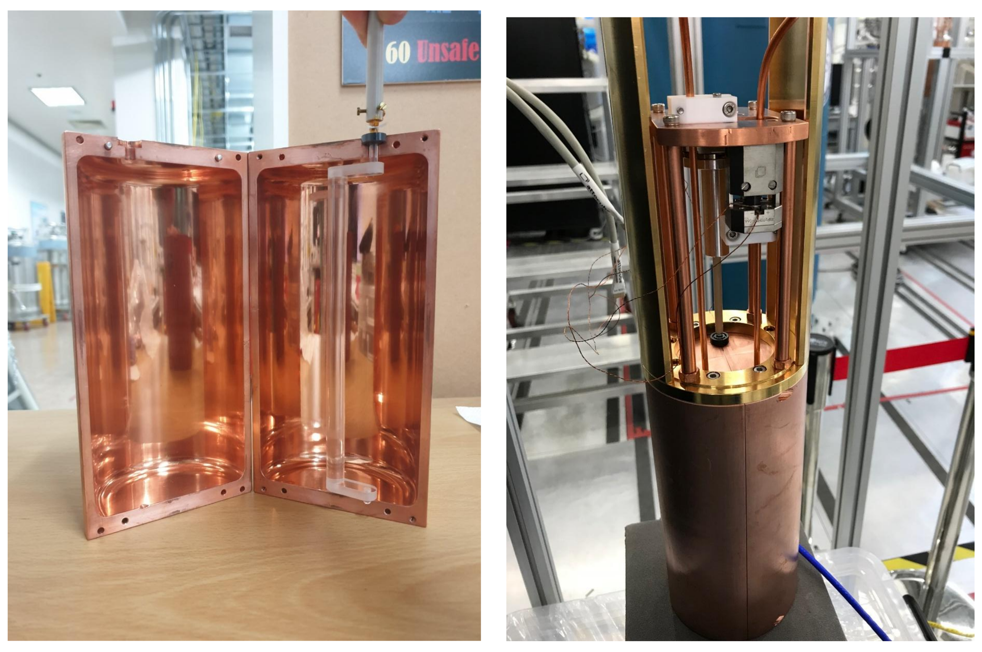


Schematics of RF chain for cryogenic system. **JPA is installed as preamplifier**

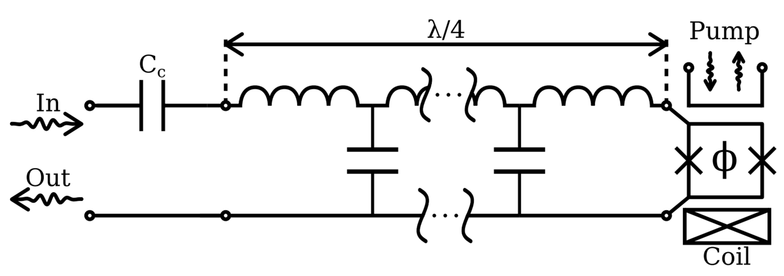
CAVITY

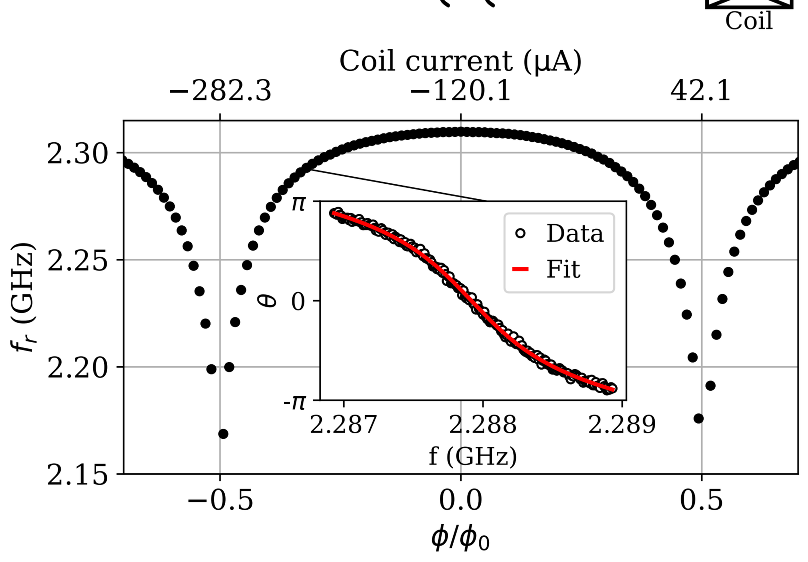
	TM_{010} w/ Tuning Rod
V [L]	1.12
f [GHz]	2.3
Q_{avg} (@50 mK)	90,000
C_{avg}	0.45

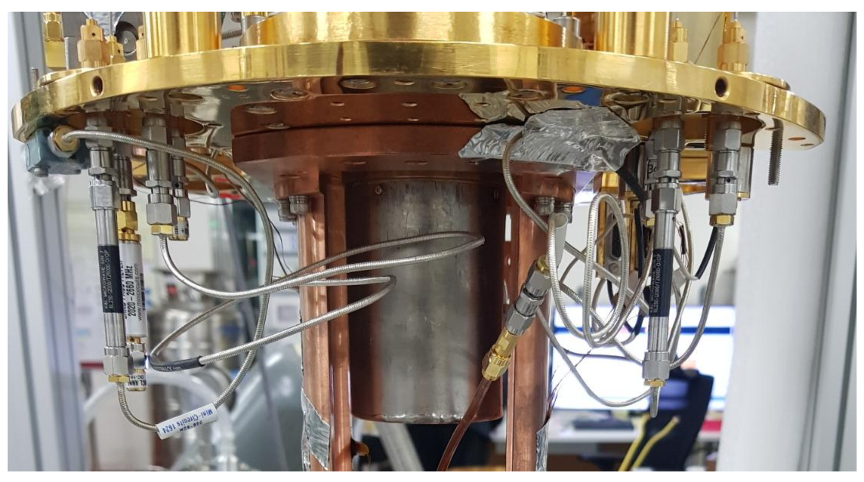
Cavity used for experiment. Volume is optimized to fit to the magnet bore.

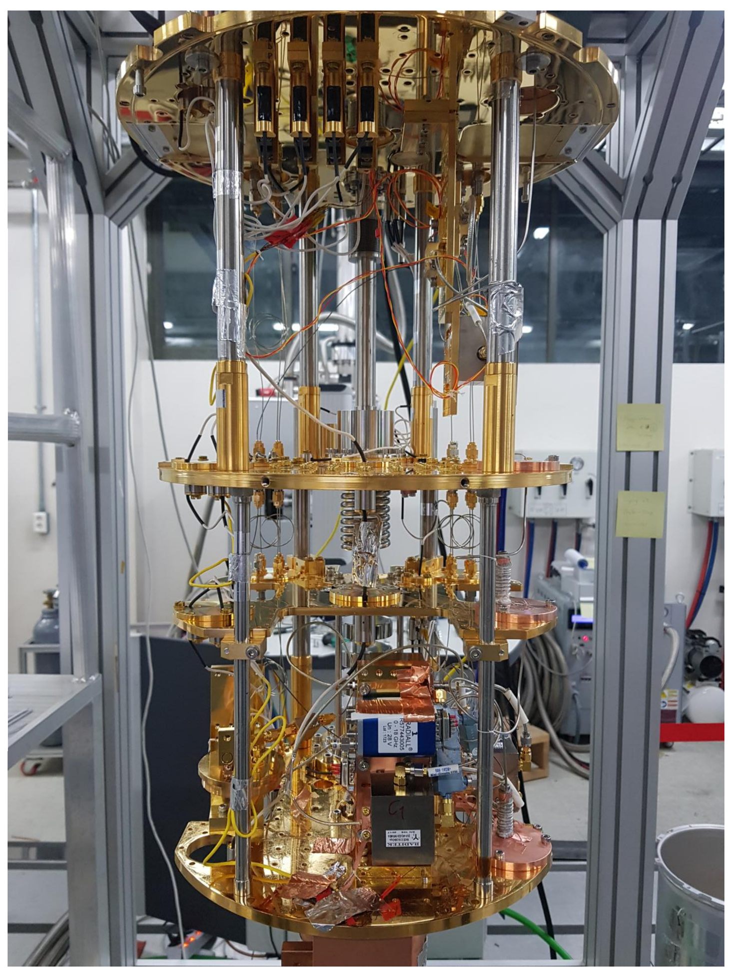


JOSEPHSON PARAMETRIC AMPLIFIER (JPA)



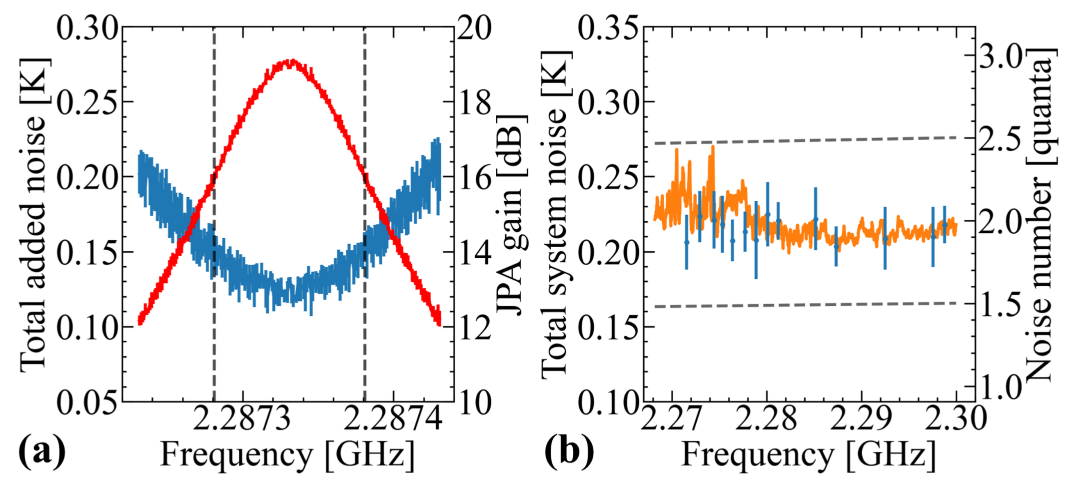




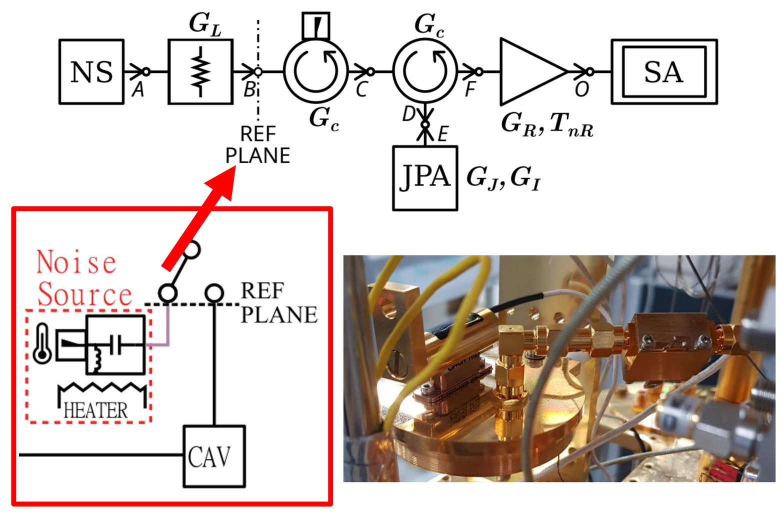


(upper left 1) Schematic of flux-driven JPA[3]
(upper left 2) Measurement result of passive resonance vs. magnetic flux[3]
(left) JPA with magnetic shield installed to dilution refrigerator
(Above) Whole chain with cavity & JPA

NOISE MEASUREMENTS



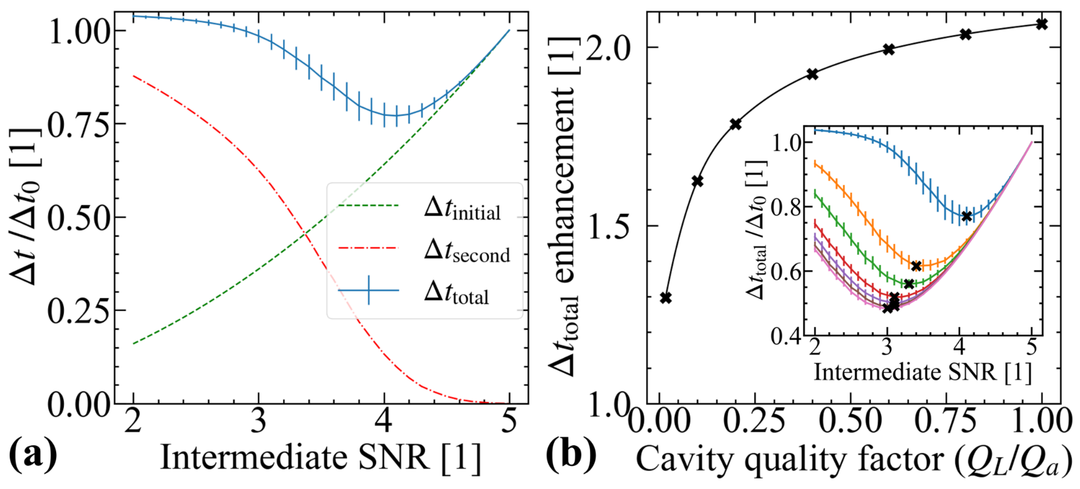
(a) Measurement result of noise and gain of the system. Blue curve corresponds to the total added noise, while orange curve refers to gain of JPA.
(b) Comparison of the tracked noise from the spectrum data and cross-check measurements. The orange curve shows the tracked noise. Blue dots represent the cross-check results.



- Measured T_{add}: 129 mK
- Temperature of cavity: 59 mK
- T_{phy}: 75 mK

→ **T_{sys}: 204 mK**
→ **~5 times better T_{sys} than 2018 run[4]**
→ **~25 times improved in scanning rate**

OPTIMIZATION OF SCANNING TIME



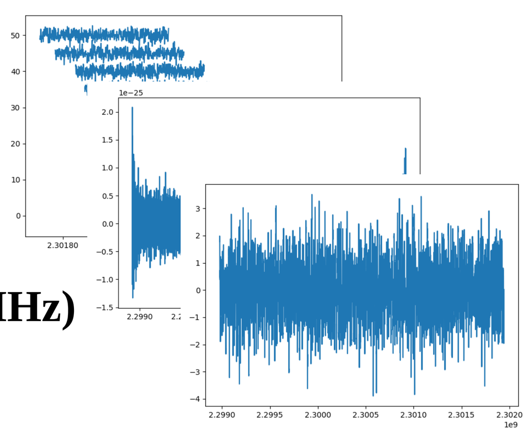
(a) Simulation of the total scan time as a function of intermediate SNR, when applying a two-stage scanning method with a cavity that has a loaded quality factor of 30,000.

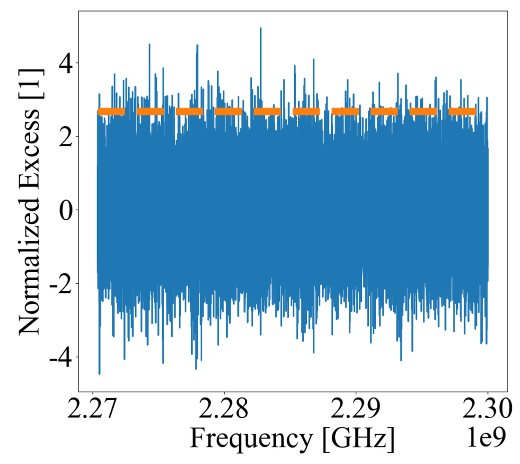
(b) Enhancement in scan speed with respect to the loaded quality factor of the cavity (Q_L), which is normalized to the quality factor of the axion (Q_a). The inset shows the simulation results using the same method as in (a), but with various Q_L values.

Scanning time is saved if the conventional scan is split to two scans, and the intermediate threshold is inserted in between. It is possible to find intermediate SNR that requires minimum total time.
→ **Minimum time required around intermediate SNR = 4.2 (For the case of this run)**
→ **Boosted scanning rate about 30%**

RUN & ANALYSIS

Run 1 period: 04.01.20 ~ 05.11.20
Run 2 period: 09.05.20 ~ 09.18.20
Avg: 7 & 5 min. per tuning step
Tuning step: 12 kHz
Swept region: 2.27 ~ 2.3 GHz (30 MHz)
→ 1,168 surviving bins (SNR = 4.2)

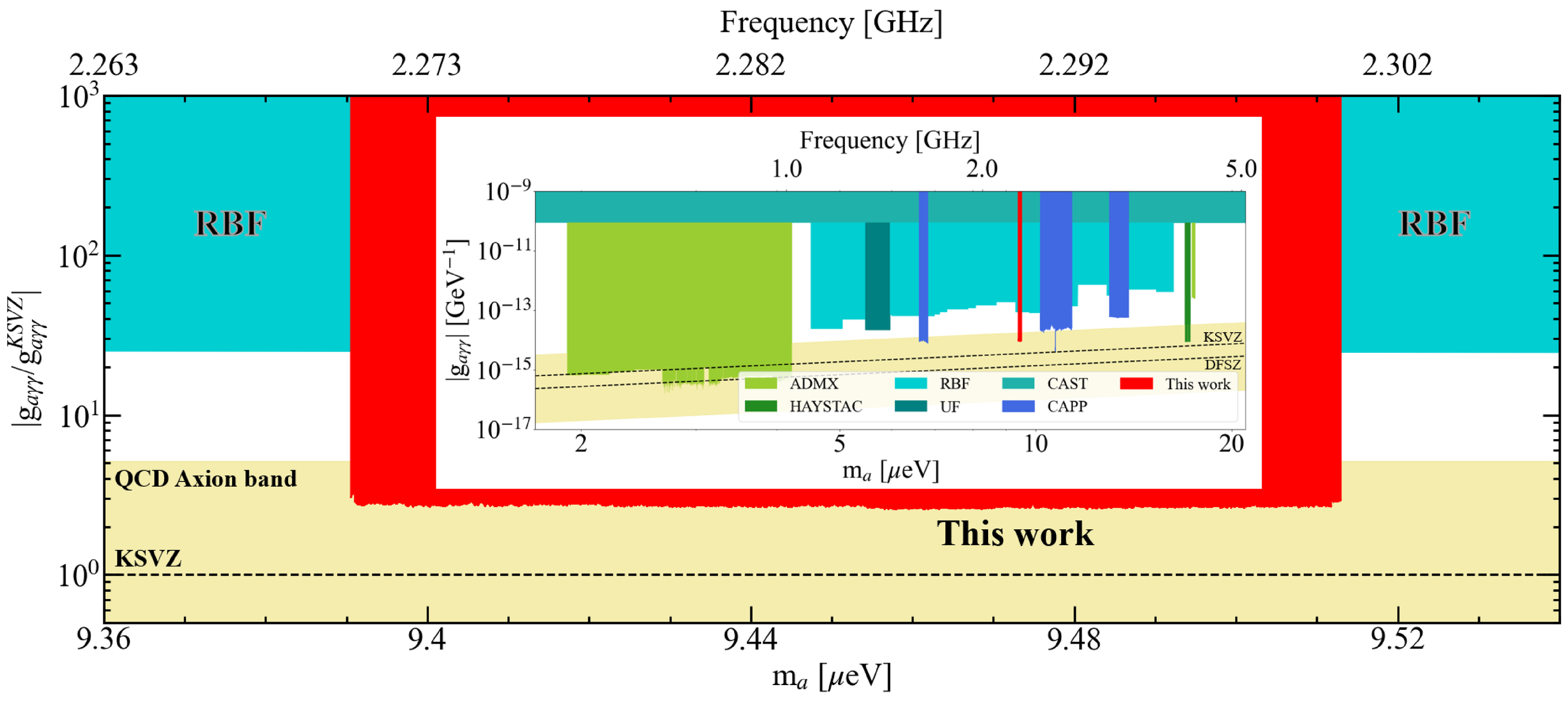




Normalized power excess after the initial scan. Orange dashed line shows the threshold for the second scan.

Second scan: Scan until SNR reaches 5
→ 46 axion candidates were found
After rescan all bins were rejected (90% confidence)

CAPP PROJECTED SENSITIVITY



CONCLUSION

- To enhance scanning rate JPA is introduced to the RF chain as quantum amplifier.
- All components including cavity, JPA are installed to the dilution refrigerator system.
- Total system noise with JPA is ~200 mK, which is around 5 times better than 2018 run.
- Scanning time is optimized by aiming for 4.2σ axion, which enables to run experiment ~30% faster.
- For 2.27 – 2.3 GHz range axion is excluded with 2.7 KSVZ sensitivity (90% confidence)

References
[1] R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38, 1440 (1977)
[2] Sikivie, P. Phys. Rev. Lett. 51.16 (1983): 1415.
[3] **Kutlu, Çağlar**, et al. "Characterization of a flux-driven Josephson parametric amplifier with near quantum-limited added noise for axion search experiments." *Superconductor Science and Technology* (2021).
[4] **Kwon, Ohjoon**, et al. "First Results from an Axion Haloscope at CAPP around 10.7 μ eV." *Physical Review Letters* 126.19 (2021): 191802.