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Axion and Precision
Physics Research

Search for QCD axion dark matter around 24.5 μeV using an 8-cell microwave resonant cavity haloscope and a flux-driven Josephson Parametric Amplifier

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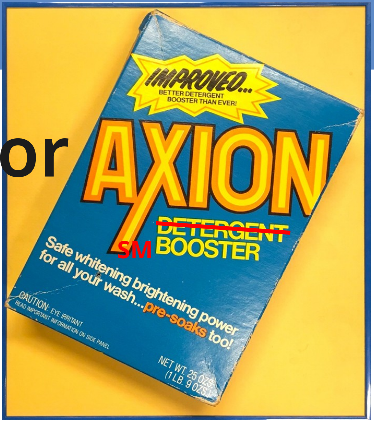
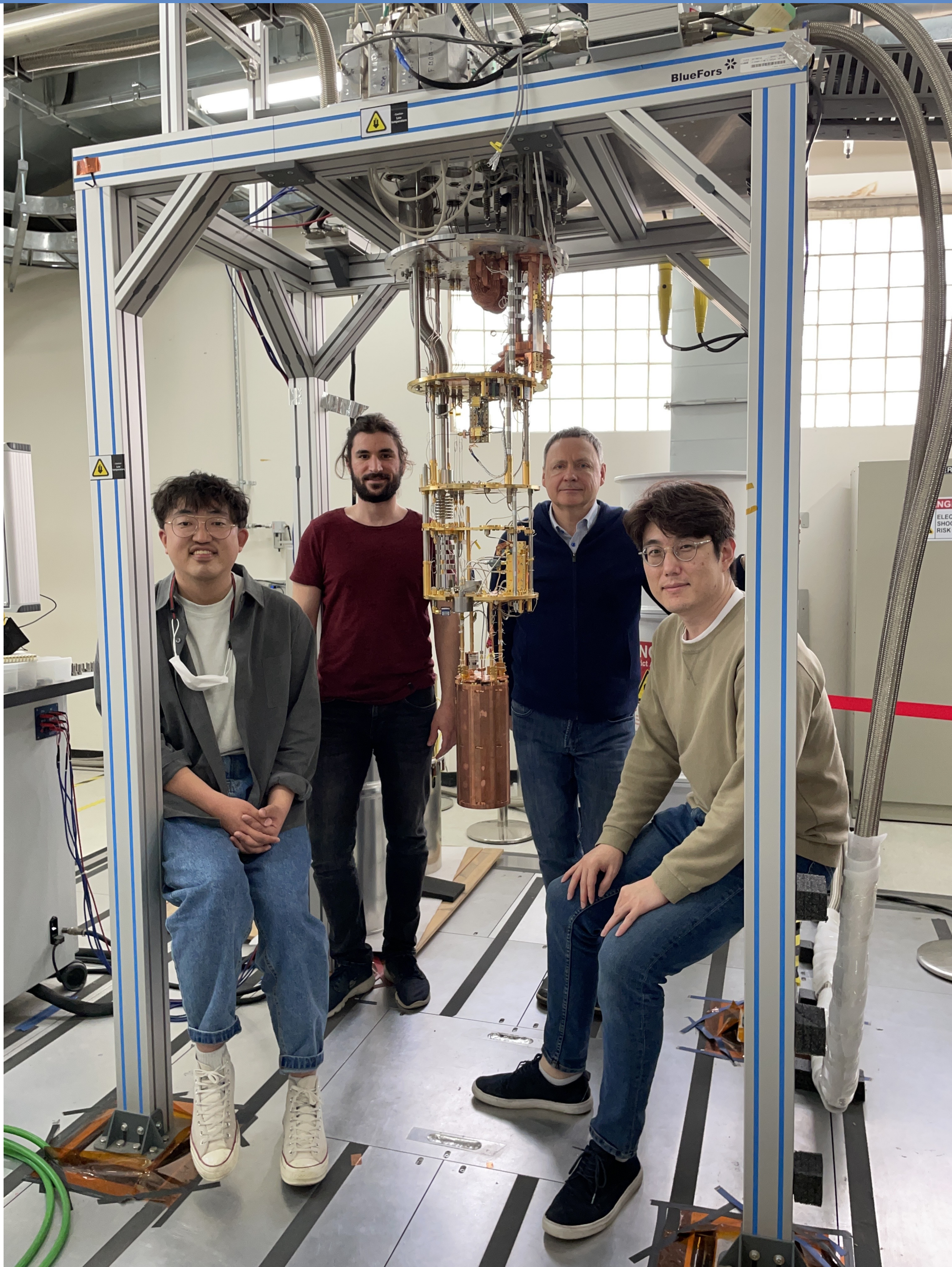
Outline



1. The search for
2. Haloscope
3. Experiment
    a. Scheme
    b. Implementation
    c. Results
4. Conclusion



The search for axion

Strong CP problem

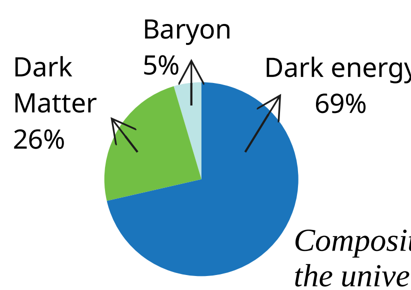
- Matter-antimatter symmetry → CP violation from somewhere
- QCD predicts CP violation with parameter $\bar{\theta}$, expected to be O(1)
- Neutron EDM experiments → $\bar{\theta} < 10^{-10}$
- $\bar{\theta}$ being small is the *strong CP* problem

> The most widely accepted solution to strong CP is given by Peccei & Quinn.
>
> They introduced a new symmetry term into the QCD lagrangian, leading to a new particle: *Axion.*

- The original PQWW* axion was ruled out by experiment [1].
- Two mainly used axion models are the KSVZ* and the DFSZ* models [1].

Dark matter

- 26% of the known universe consists of dark matter
- Cold dark matter model is widely adopted (ΛCDM model)



Composition of the universe [2]

> Axions can give correct DM abundance given that:
>
> Early universe produces cold axions
>
> Axions are weakly interacting and very stable

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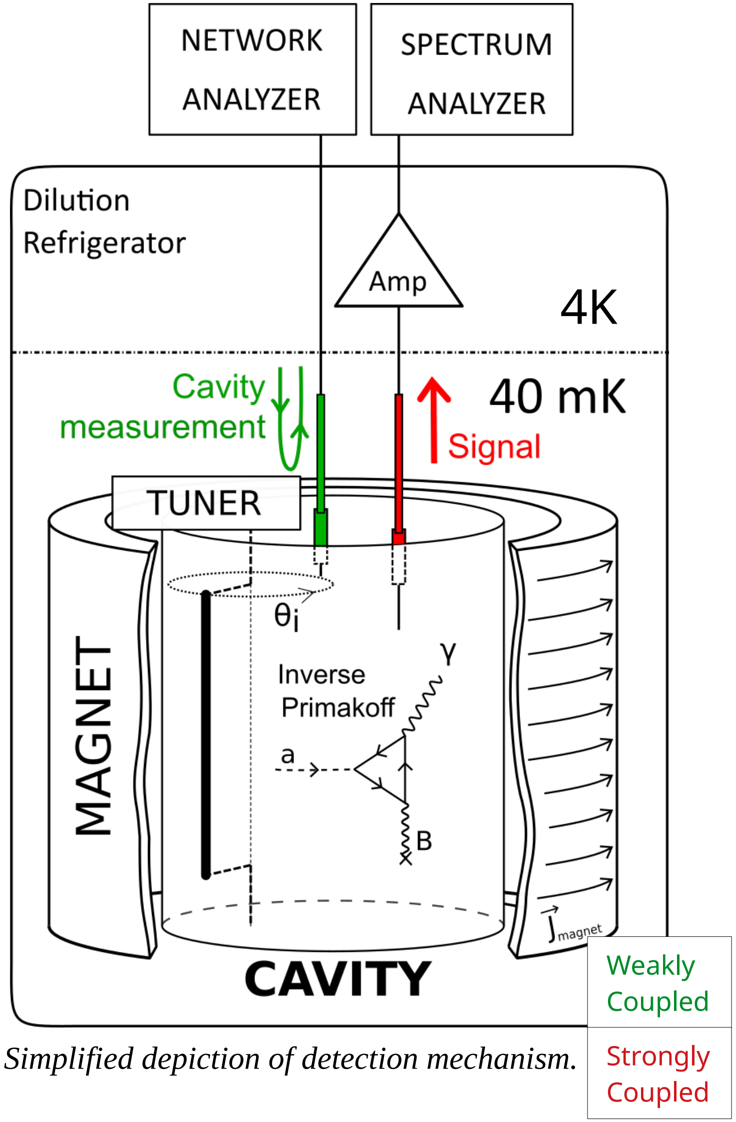
[1] David J.E. Marsh, Axion cosmology, Physics Reports, Volume 643, 2016, Pages 1-79, ISSN 0370-1573, https://doi.org/10.1016/j.physrep.2016.06.005.
[2] Planck Collaboration, "Planck 2018 results. VI. Cosmological parameters" arXiv:1807.06209v1. Preprint.

* PQWW: Peccei-Quinn-Weinberg-Wilczek. KSVZ: Kim-Shifman-Vainshtein-Zakharov. DFSZ: Dine-Fischler-Srednicki-Zhitnitsky

Haloscope Detectors



Simplified depiction of detection mechanism.

Lagrangian for the axion-photon coupling interaction term:

$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \mathbf{E}\cdot \mathbf{B}$$

Consequently, axions are converted into microwave photons and resonantly detected via the antenna [1]

Signal power coupling to the antenna[2] :

$$P_a = \frac{\alpha^2 \hbar^3 c^3}{\mu_0 \Lambda^4 \pi^2} V B_0^2 C_{nlm} g_\gamma^2 \rho_a \frac{\beta}{1+\beta} \frac{f Q_L}{1+(2Q_L \delta f/f_0)^2}$$

V: Volume of the cavity.
B_0: Magnetic field strength.
C_{nlm}: Form factor of the relevant mode.
g_γ: Unitless constant related to axion-photon coupling.
ρ_a: $0.45\,\mathrm{GeV/cm^2}$. DM axion average energy density.
Λ: 75 MeV. Coming from QCD computations.

β: Coupling coefficient of the strong port.
f: Frequency of the dissipation.
f_0: Resonant frequency of the cavity.
δf: $f - f_0$
Q_L: Loaded Q factor of the cavity.

Typically $\begin{cases} \text{Signal: } P_a \sim 10^{-23}\ \mathrm{W} \\ \text{Noise: } \sigma_n \sim 10^{-20}\ \mathrm{W}\ ! \end{cases}$

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[1] P. Sikivie, “Experimental tests of the ‘invisible’ axion,” Phys. Rev. Lett., vol. 51, pp. 1415–1417, 1983.
[2] H. Peng et al., “Cryogenic cavity detector for a large-scale cold dark-matter axion search,” Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip., vol. 444, pp. 569–583, 2000.

Haloscope Detectors: Scanning Rate

The mass is unknown → Need to scan frequencies.
Figure of merit for a haloscope detector,
the scanning rate:

Model constant (KSVZ/DFSZ)

DAQ Efficiency

Cavity design

$$S \propto \frac{g_\gamma^4}{\mathrm{SNR}^2} \eta \frac{1}{T_s^2} B_0^4 V^2 C_{nlm}^2 f_0^2 Q_L$$

Detector capability

Target signal to noise ratio for discovery

System noise temperature

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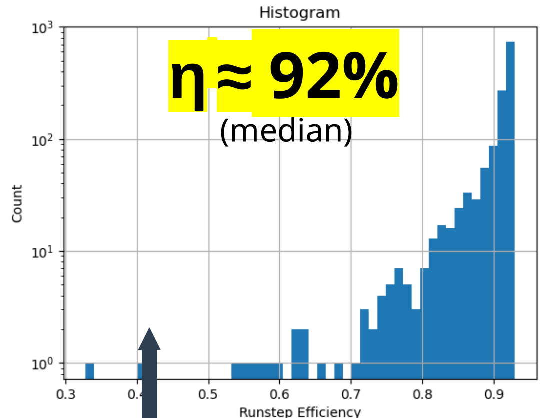
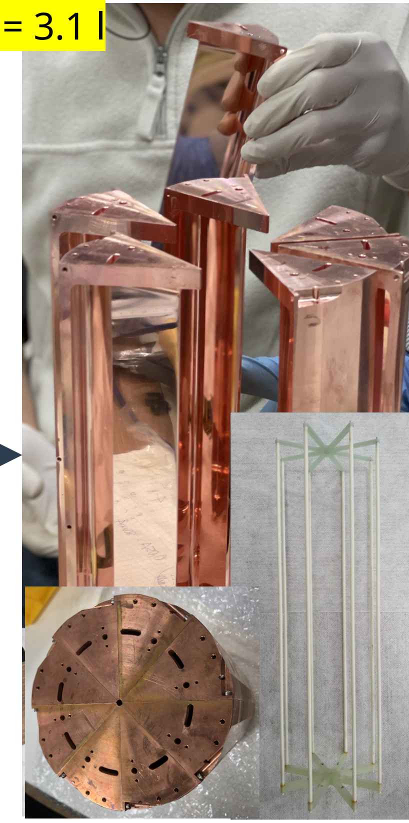
Experiment

Bluefors LD400
Dilution Refrigerator

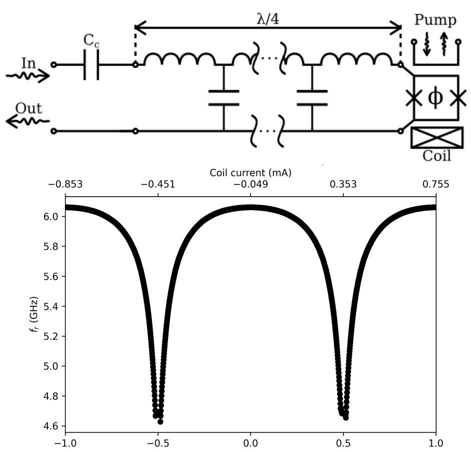


Unique 8-Cell microwave cavity
V = 3.1 l



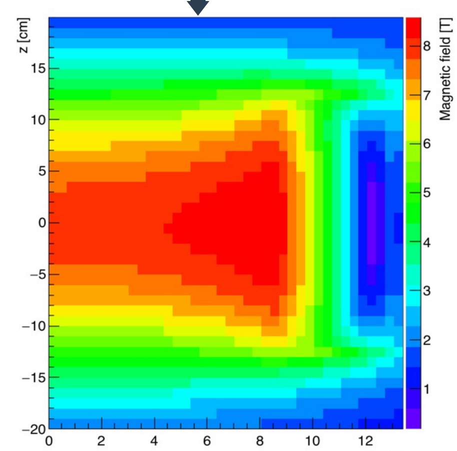
$$S \propto \frac{\eta}{T_s^2} B_0^4 V^2 C_{nlm}^2 f_0^2 Q_L$$

Flux-pumped JPA



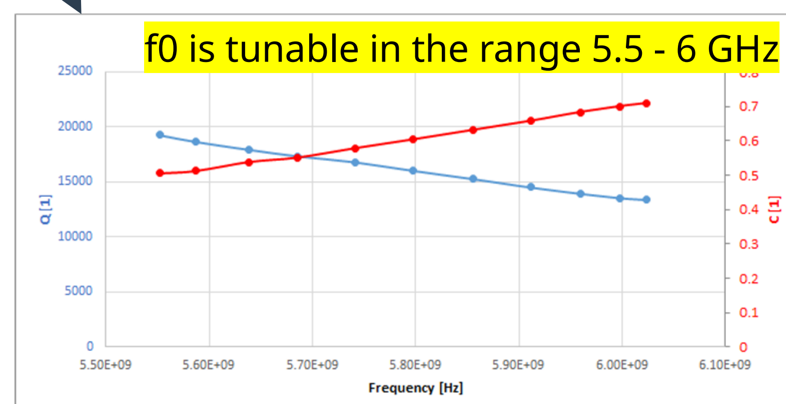
~0.41K

B_0~6.96T



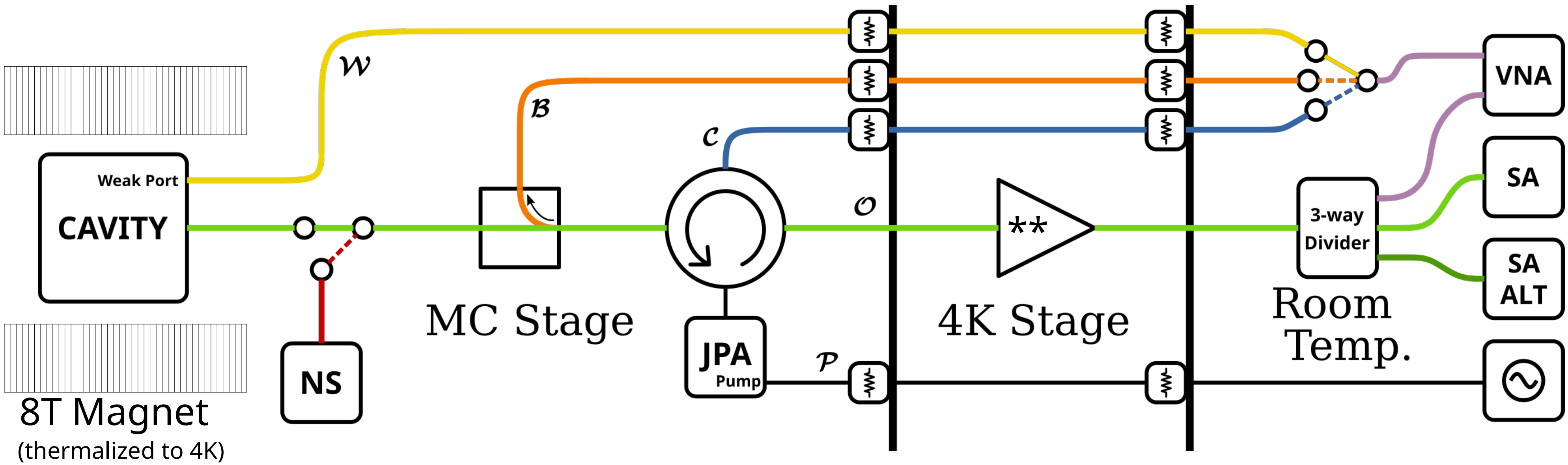
AMI 8T superconducting magnet
with 16.5cm clear bore

f0 is tunable in the range 5.5 - 6 GHz



In collaboration with
Univ. of Tokyo/RIKEN

Simplified Measurement Diagram*



- $T_{MC} \sim T_{CAV}$ = 40 mK during whole experiment.

VNA: Vector Network Analyzer
SA: Primary Spectrum Analyzer
SA-ALT: Alternate Spectrum Analyzer

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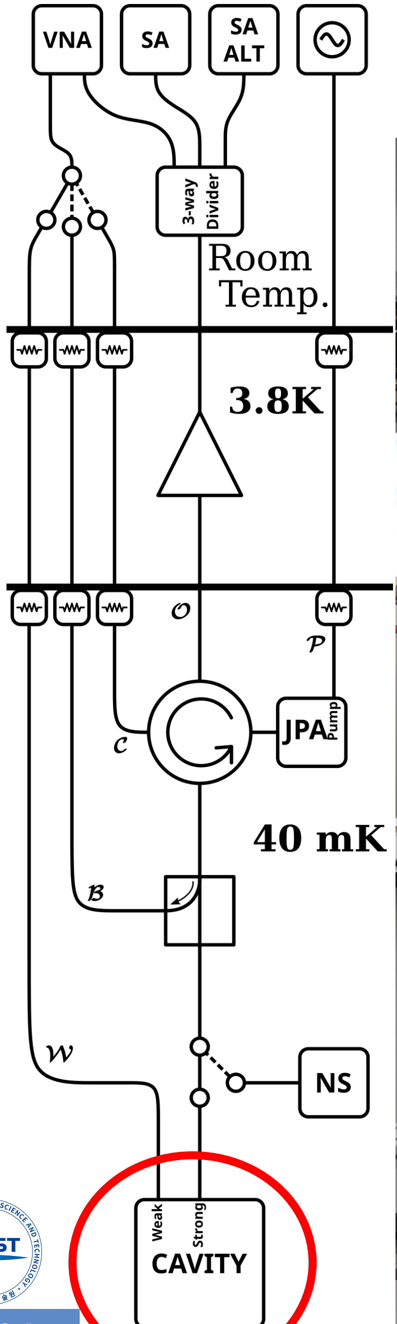
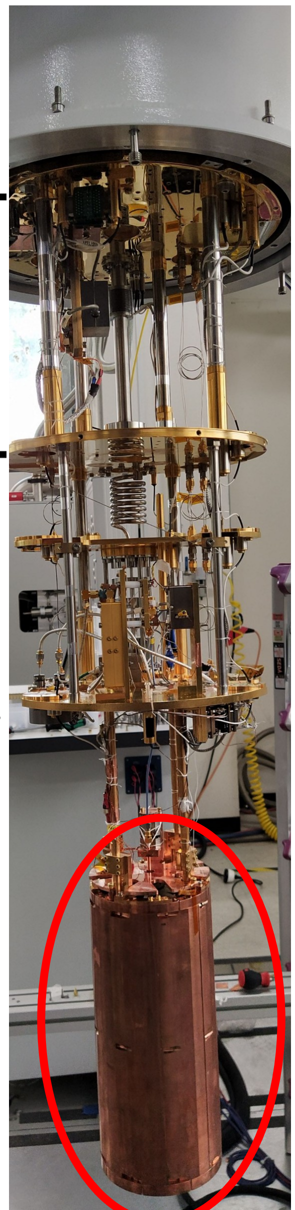
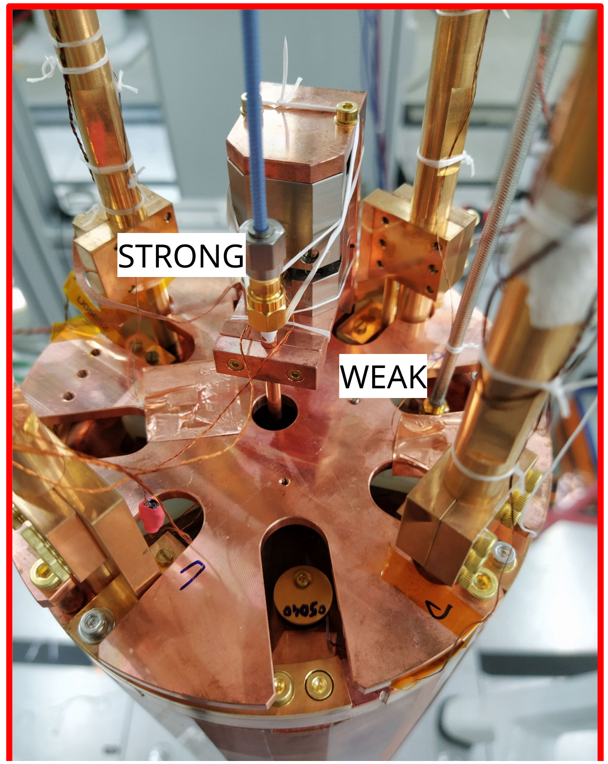
* Letters W, B, C, O and P denote *signal paths* of importance from experimentalists perspective.
** 2x Low Noise Factory cryogenic HEMT amplifiers cascaded with an isolator in between.

Implementation: Cavity





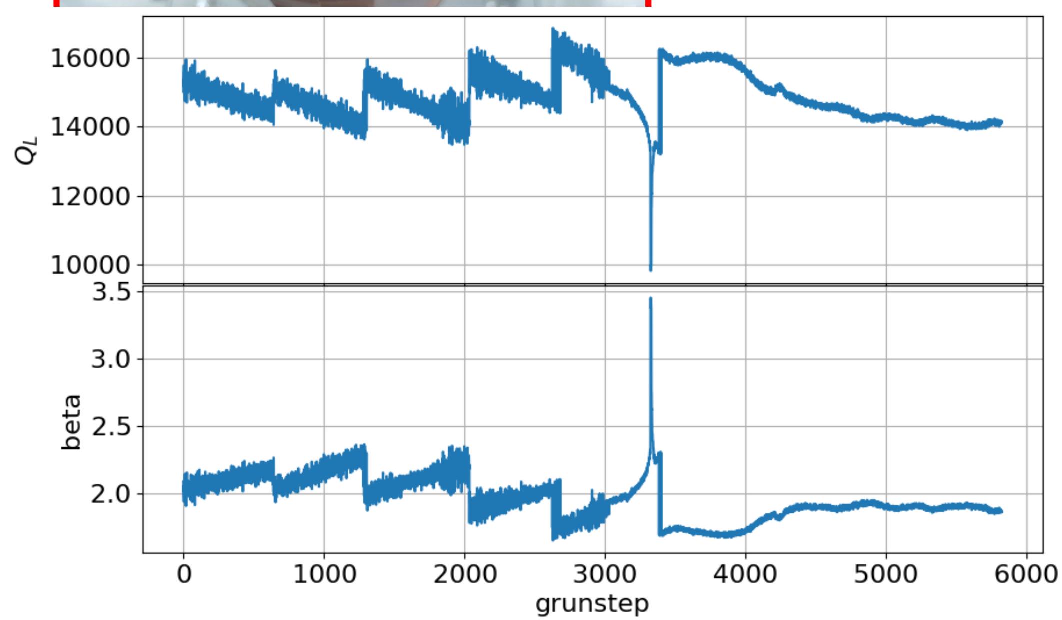


Q_0 ~45000

Q_L ~ 15000

C ~ 0.6

T_{base}~ 19 mK (25 mK @8T)



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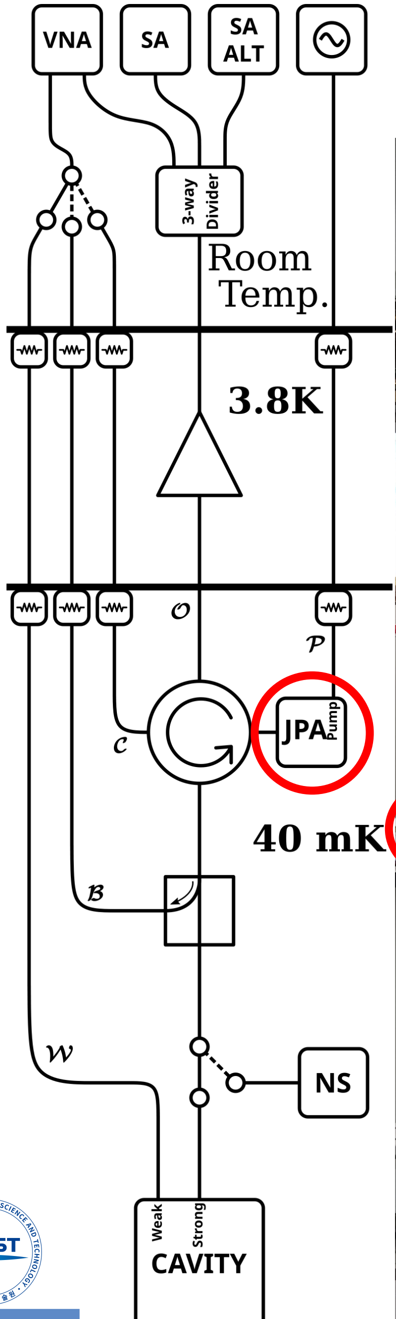
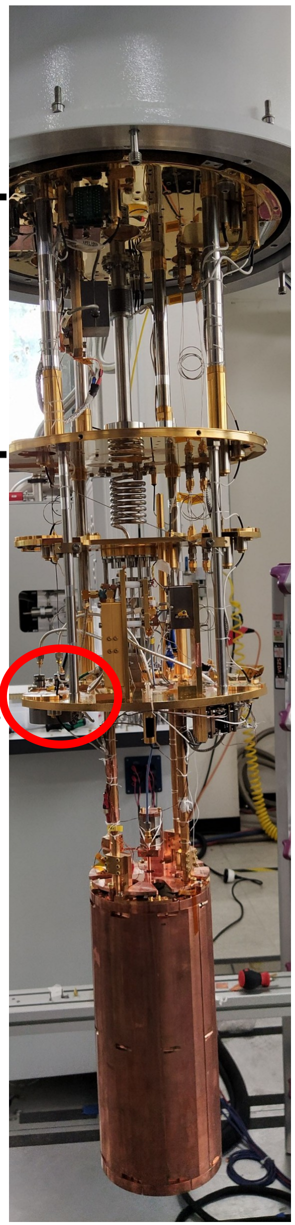
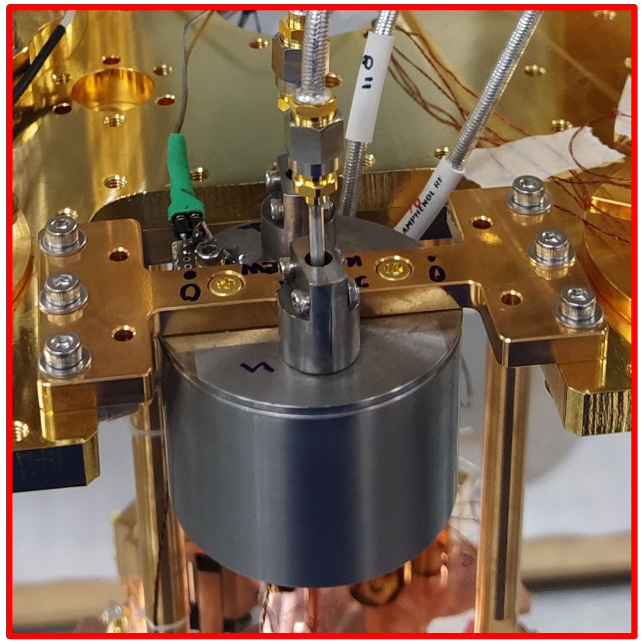
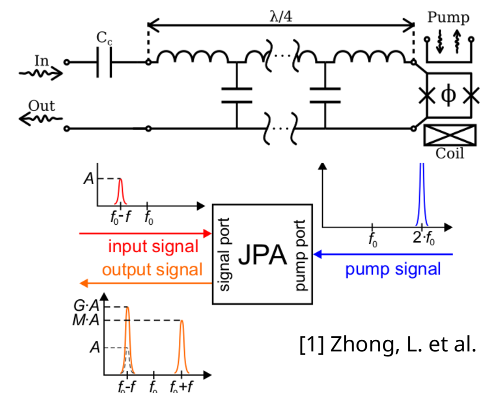
Implementation: JPA



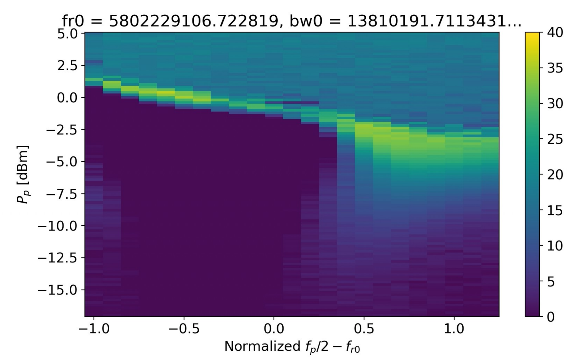


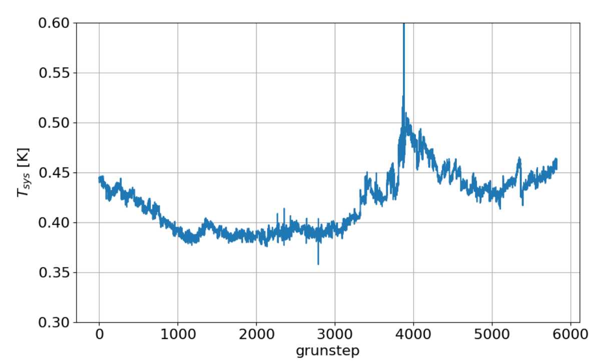


Al-μMetal-Nb: Shielding factor @8T > 1e4
Gain ~20dB
3dB bandwidth ~ 1 MHz
T_s ~ 400-450 mK



[1] Zhong, L. et al.





Tuning based on a look-up table generated from prior gain parameter maps (paramap).

[1] Zhong, L., Menzel, E. P., Di Candia, R., Eder, P., Ihmig, M., Baust, A., ... Gross, R. (2013). Squeezing with a flux-driven Josephson parametric amplifier. New Journal of Physics, 15. https://doi.org/10.1088/1367-2630/15/12/125013

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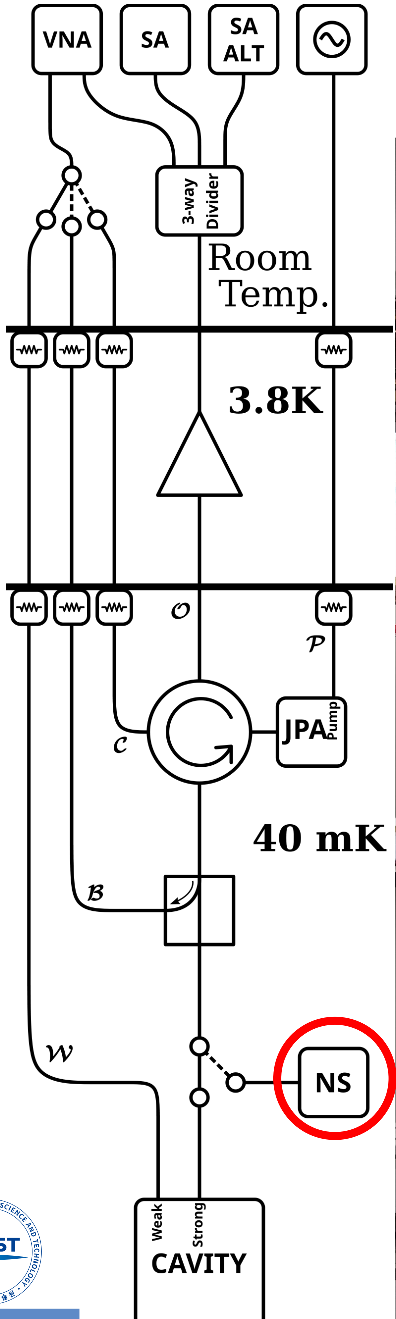
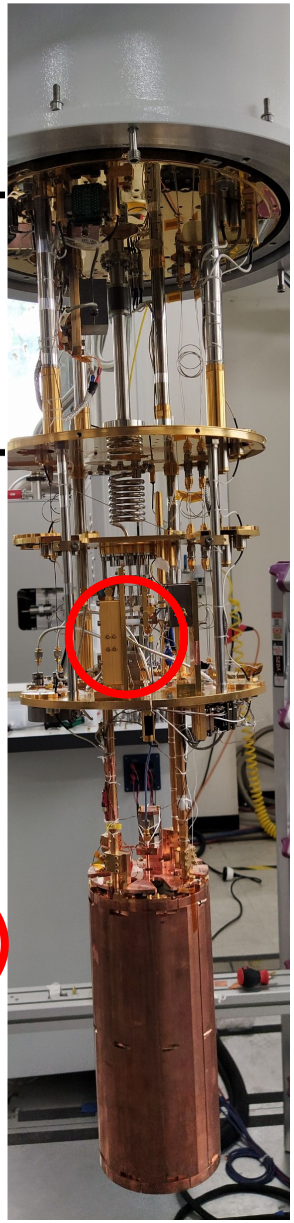
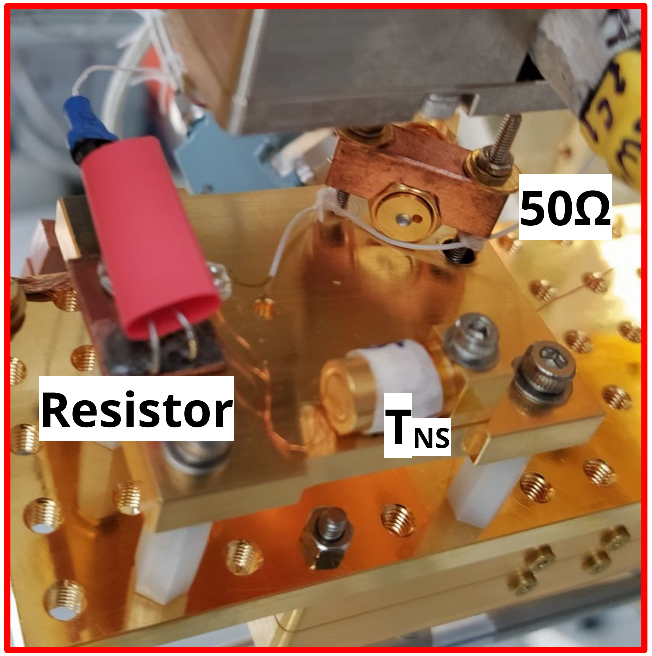
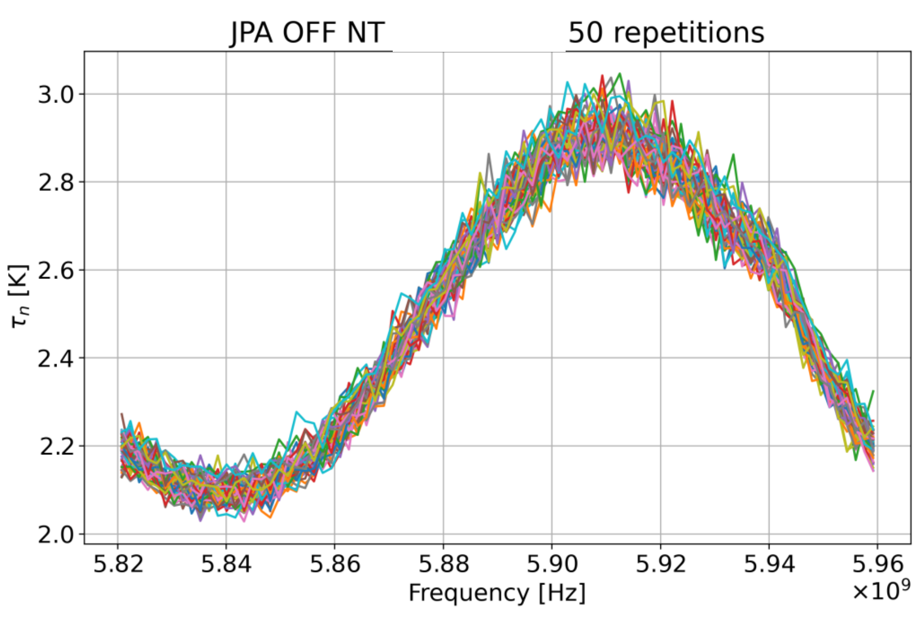




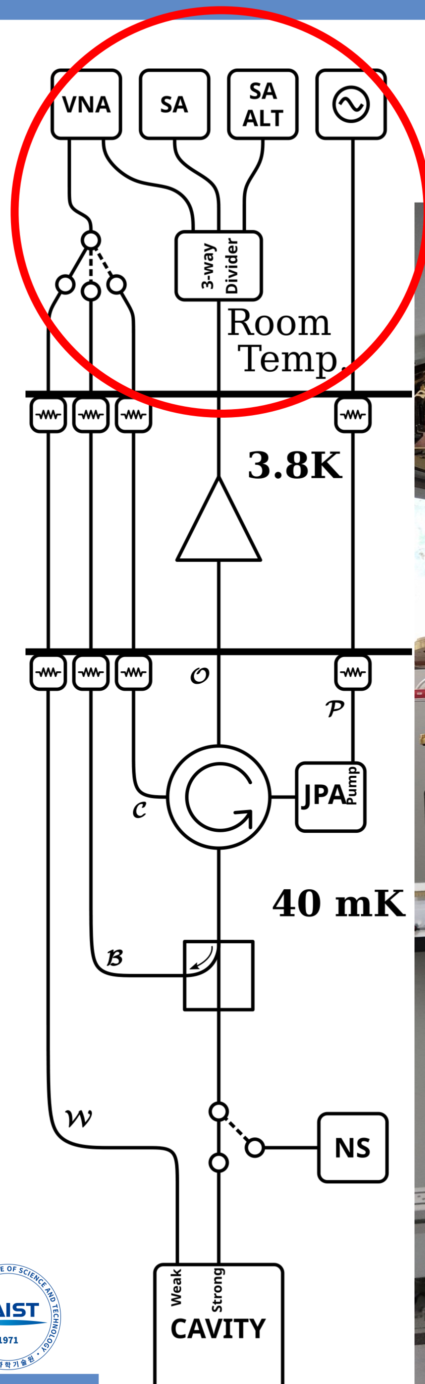


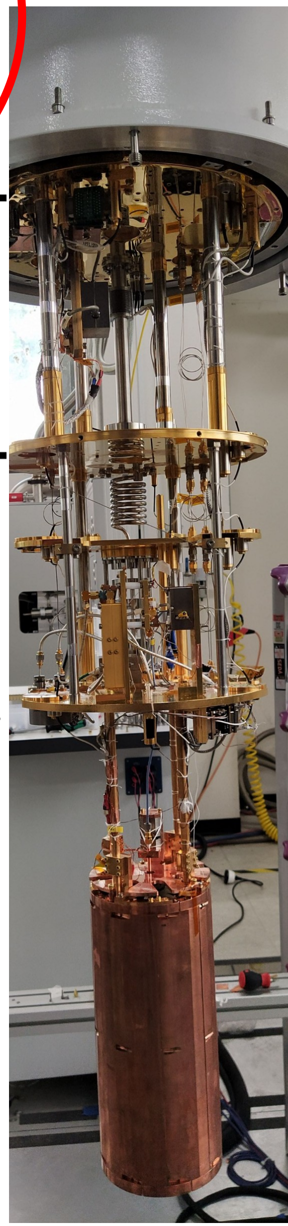
Tunable from 40 mK to 600 mK without effect on MC temperatures.

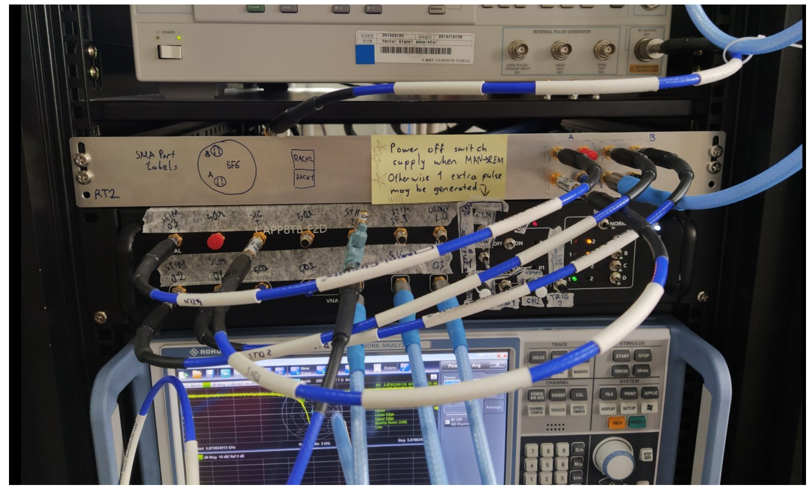
Used for noise temperature measurements in the JPA off state.



Implementation: Electronics & Signaling

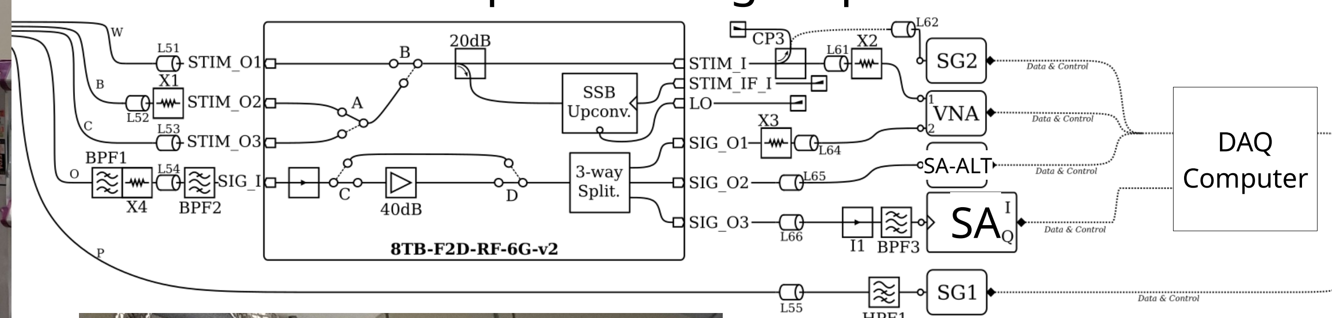






RT box houses RF and low frequency signaling electronics.

Room temperature signal path



End-to-end shielding in all cabling.

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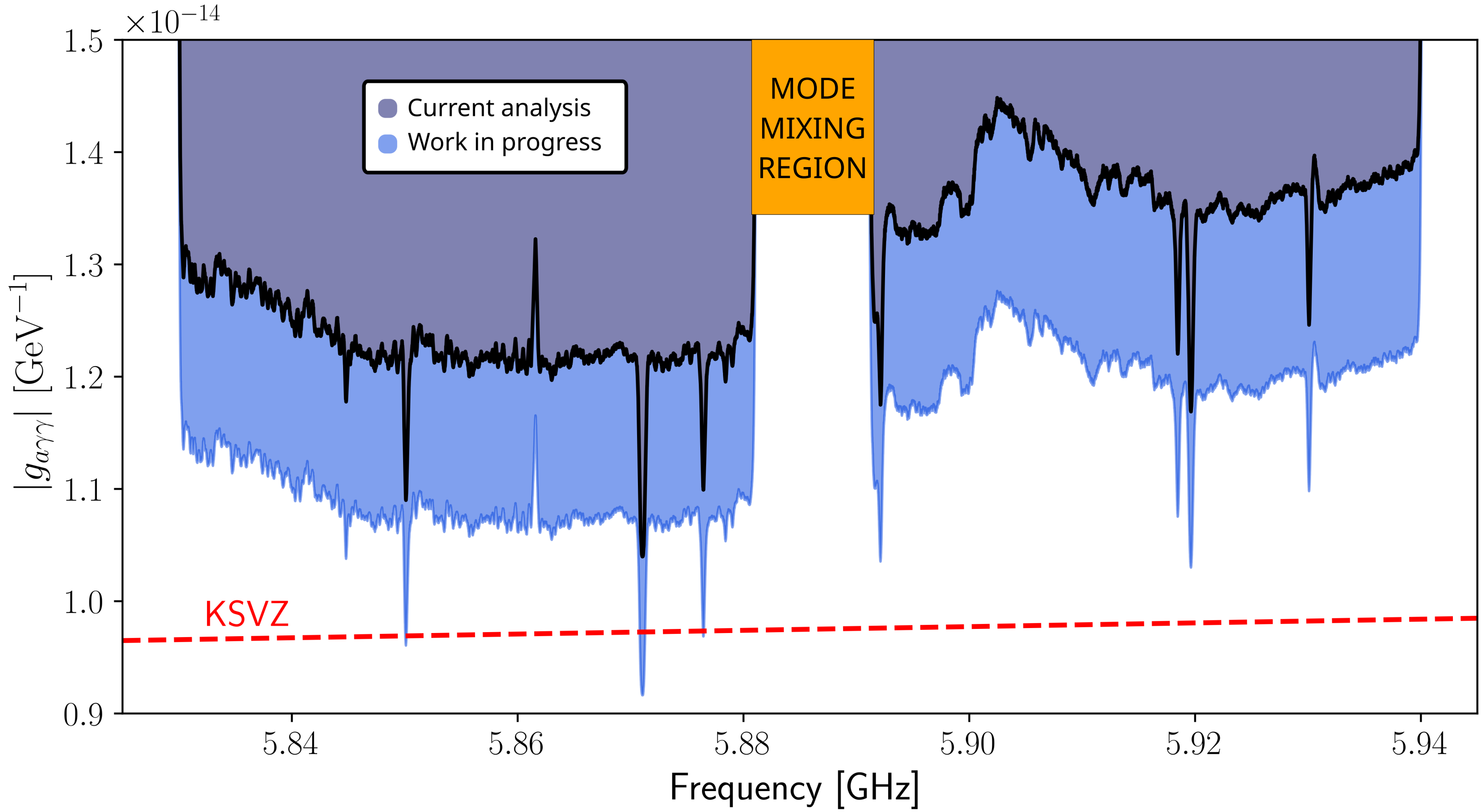
Preliminary Analysis Results

Exclusion plot with 90% confidence level*



The current analysis has about **27%** SNR loss from baseline estimation.
We are targeting to bring it down to **15%**.

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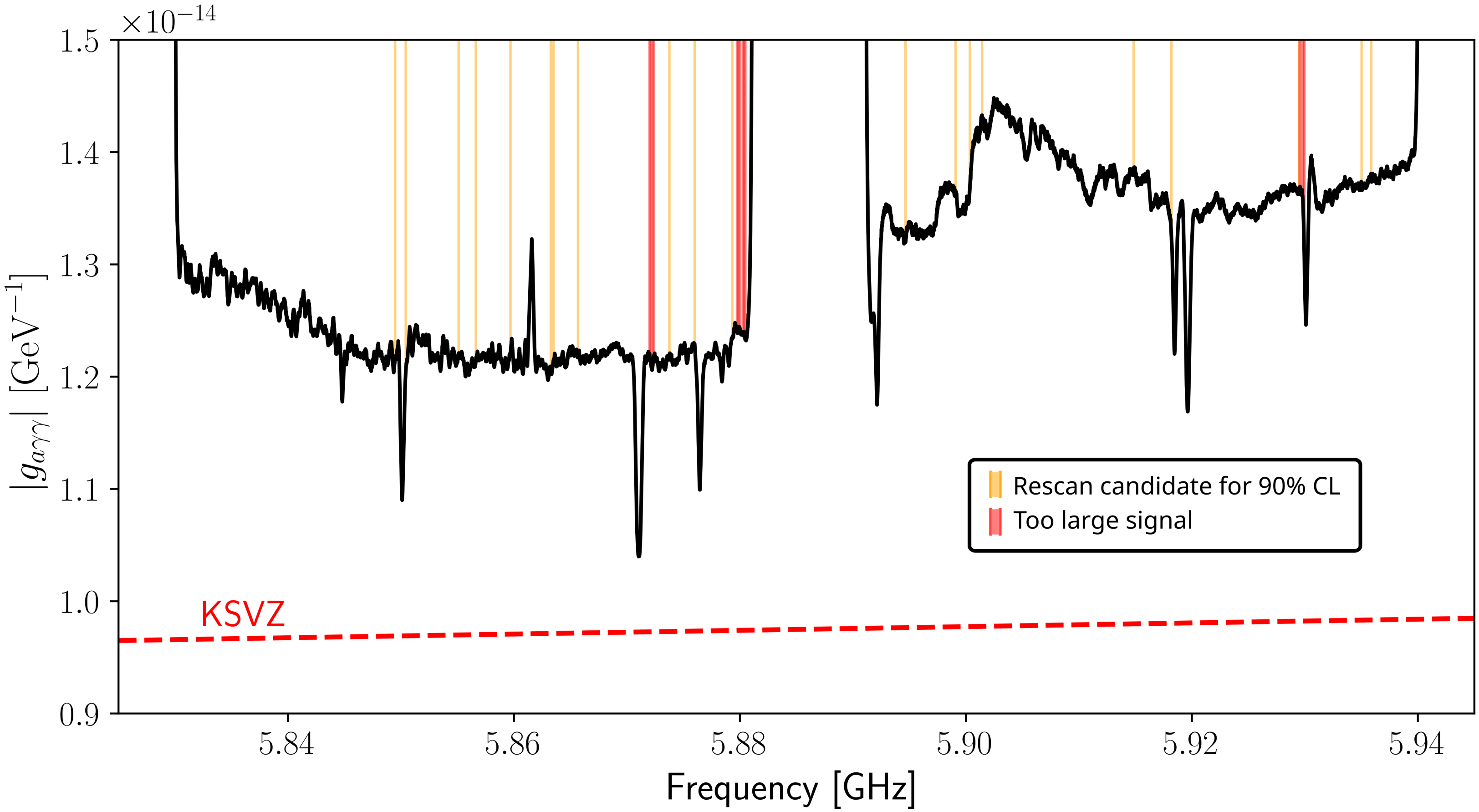
Preliminary Analysis Results

Exclusion plot with 90% confidence level*



* 21 candidates for the current analysis at 90% CL are not yet rescanned.

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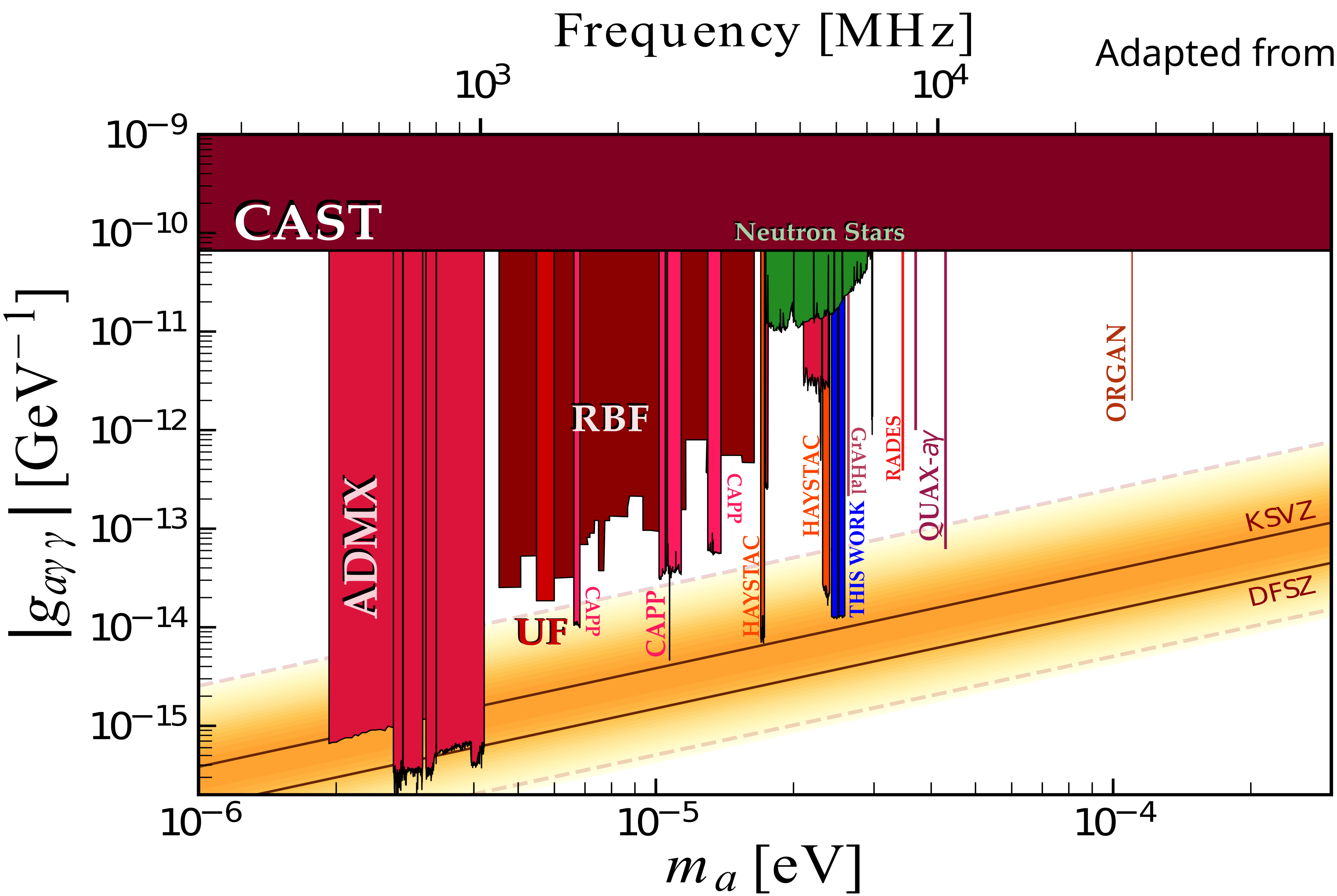
Preliminary Analysis Results

Adapted from [1]



[1] O'Hare, C. (2020) cajohare/AxionLimits: AxionLimits. Zenodo. doi: 10.5281/zenodo.3932430.

Conclusion

Highlights

- Covered a 100 MHz region around 5.885 GHz with near KSVZ sensitivity.
- Used a multi-cell cavity design in a high sensitivity experiment for the first time.
- Implemented a JPA based read-out, achieving one of the best system noise temperature for the frequency range.

What's next?

- We experienced a minor setback during June due to a chiller failure followed by a HEMT failure.
- System is recovered since the beginning of July and we are getting ready to start focusing on the candidates and observed large signals.

Thank you for listening

Any questions?

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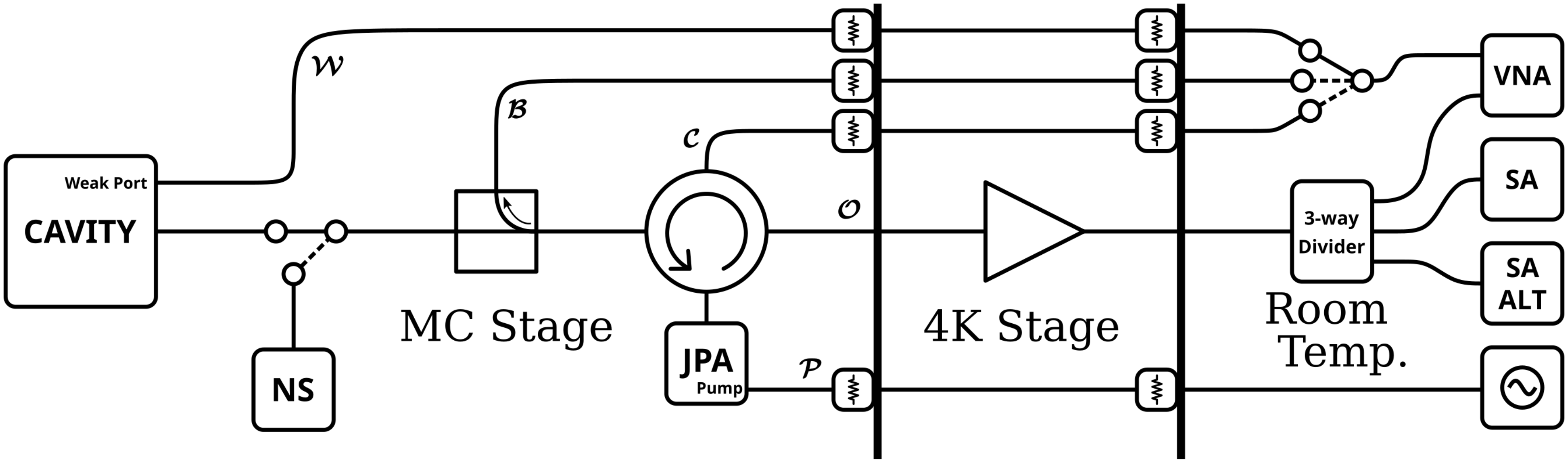
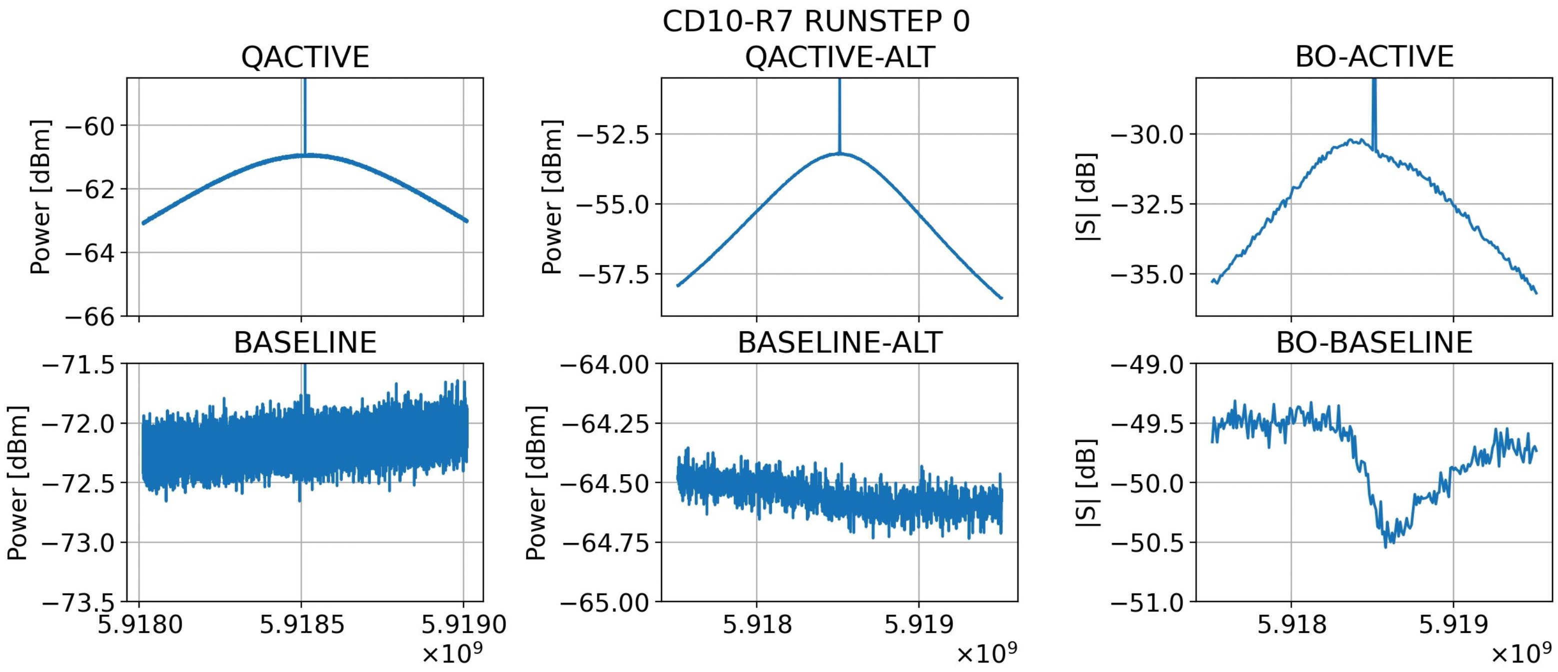
Extra: Data

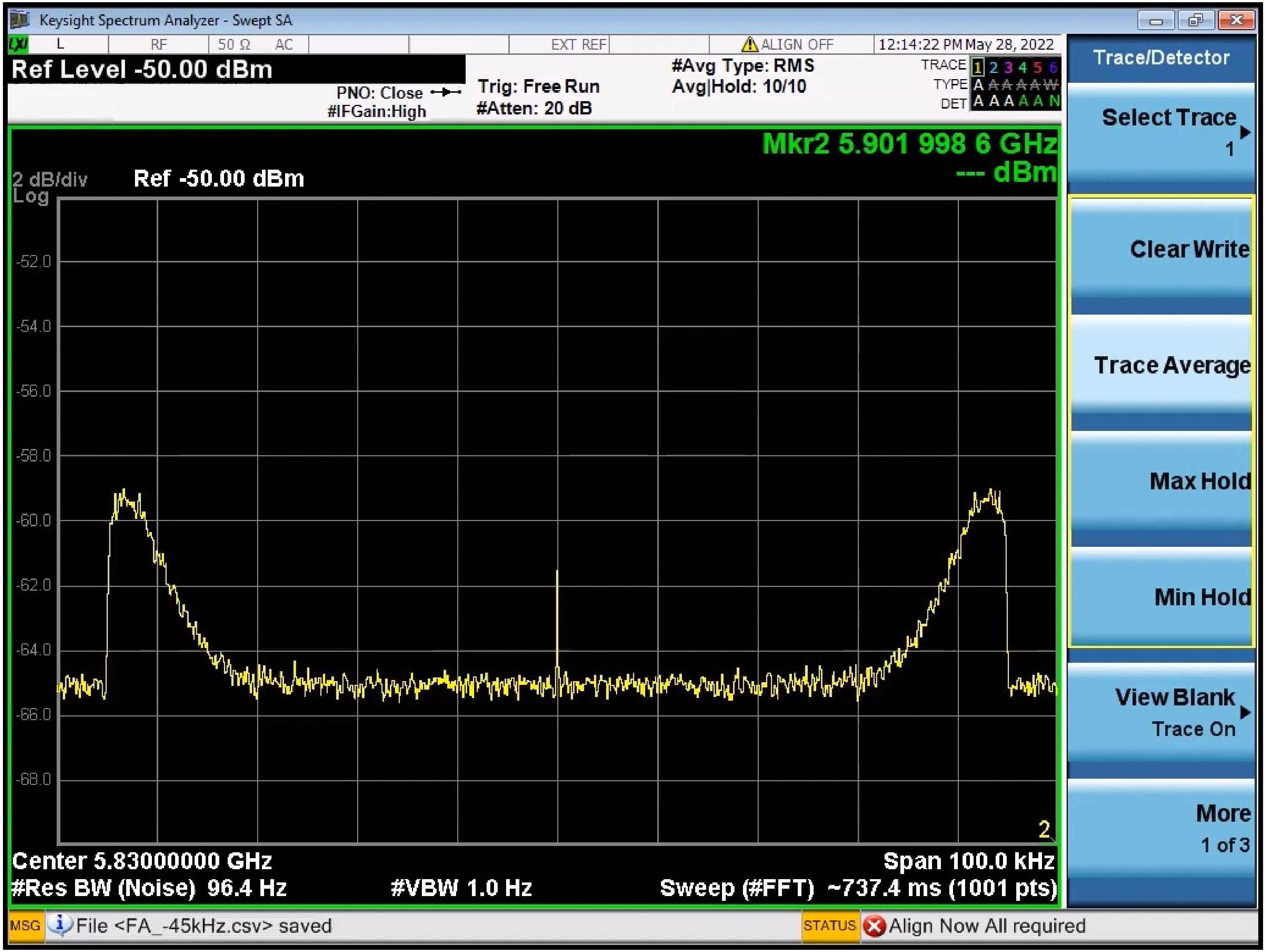


Weak Port
CAVITY
NS
MC Stage
JPA
Pump
4K Stage
Room
Temp.
3-way
Divider
VNA
SA
SA
ALT



CD10-R7 RUNSTEP 0
QACTIVE
QACTIVE-ALT
BO-ACTIVE
BASELINE
BASELINE-ALT
BO-BASELINE
Power [dBm]
|S| [dB]
×10^9

Extra: Fake Signal Demonstration



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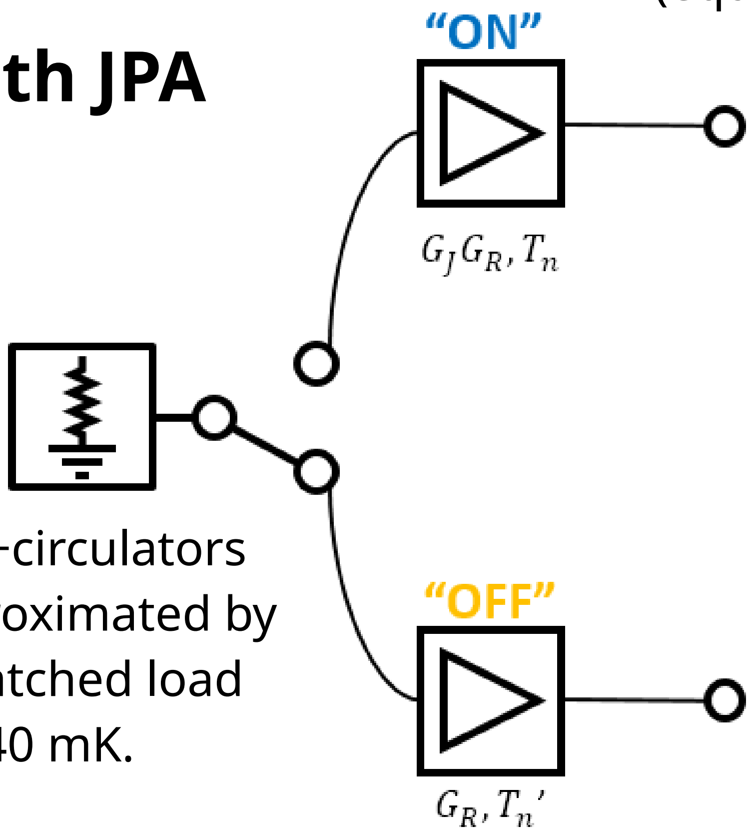
Extra: NT via Spectra Comparison

(equivalent to SNR improvement)

with JPA

Known

Unknown



$$P_O = G_J G_R (P_{nf} + T_n)$$

$$Z \equiv \frac{P_O}{P_O'} = G_J \frac{P_{nf} + T_n}{P_{nf} + T_n'}$$

CAV+circulators approximated by a matched load at ~40 mK.

$$P_O' = G_R (P_{nf} + T_n')$$

Measured using noise source.

$$(k_B B = 1)$$

$$P_n(f, T) = hfB\left[\frac{1}{\exp\left(\frac{hf}{k_B T}\right) - 1} + \frac{1}{2}\right]$$

$$P_{nf} \equiv P_n(f, T_{MC})$$

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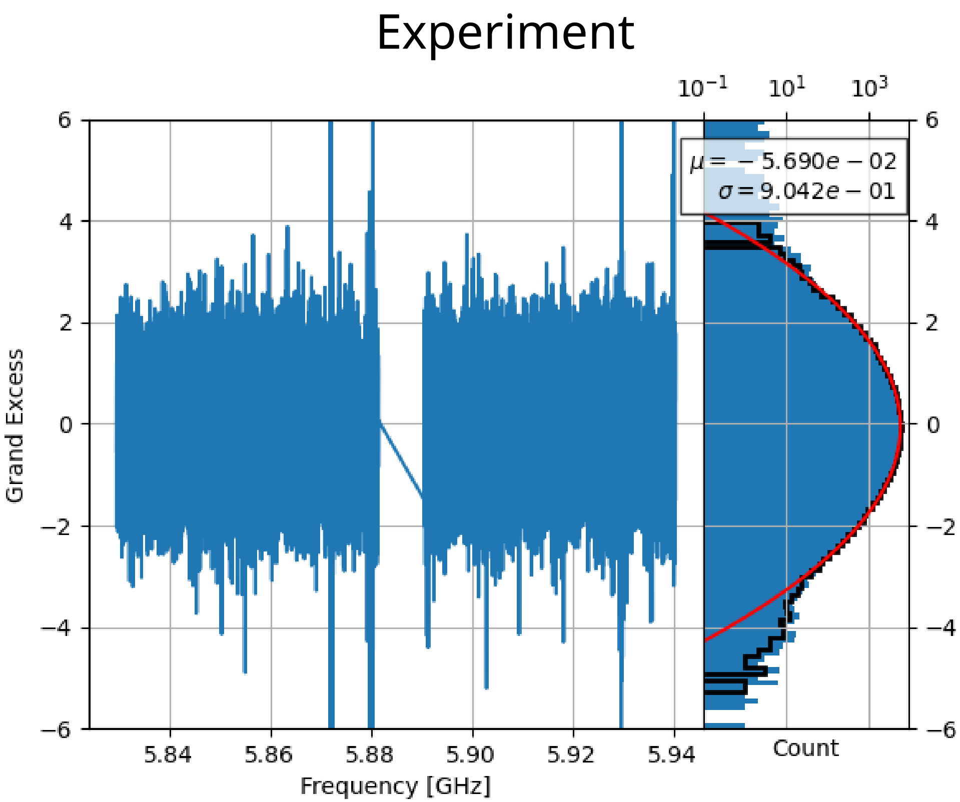
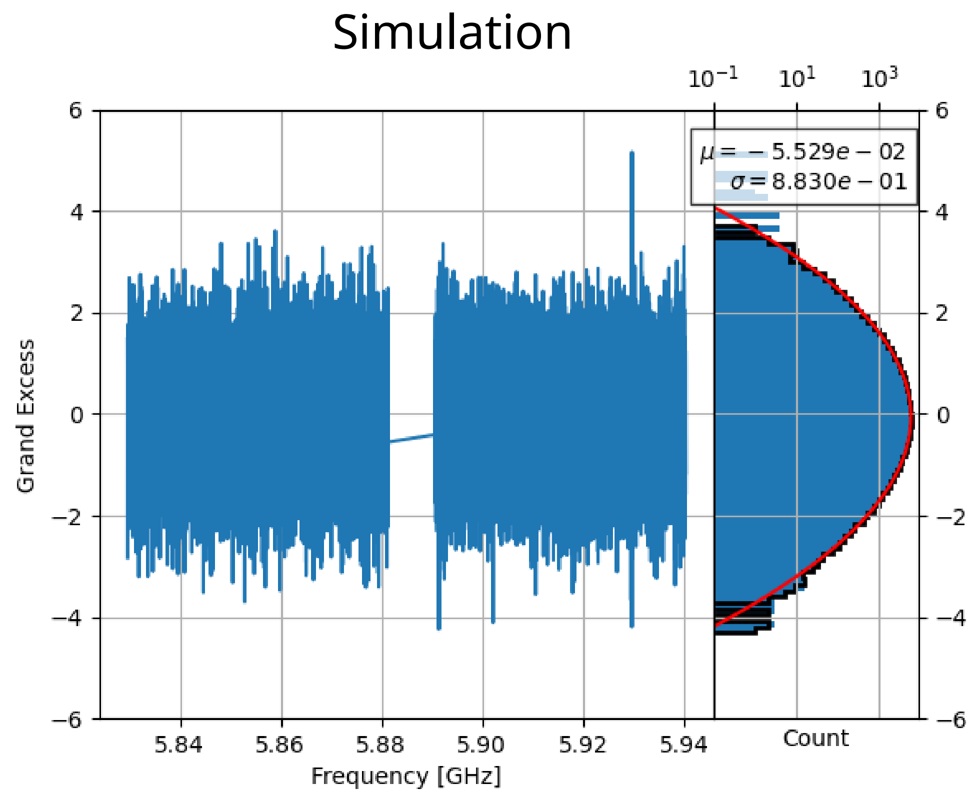
Extra: Grand Excess Spectrum





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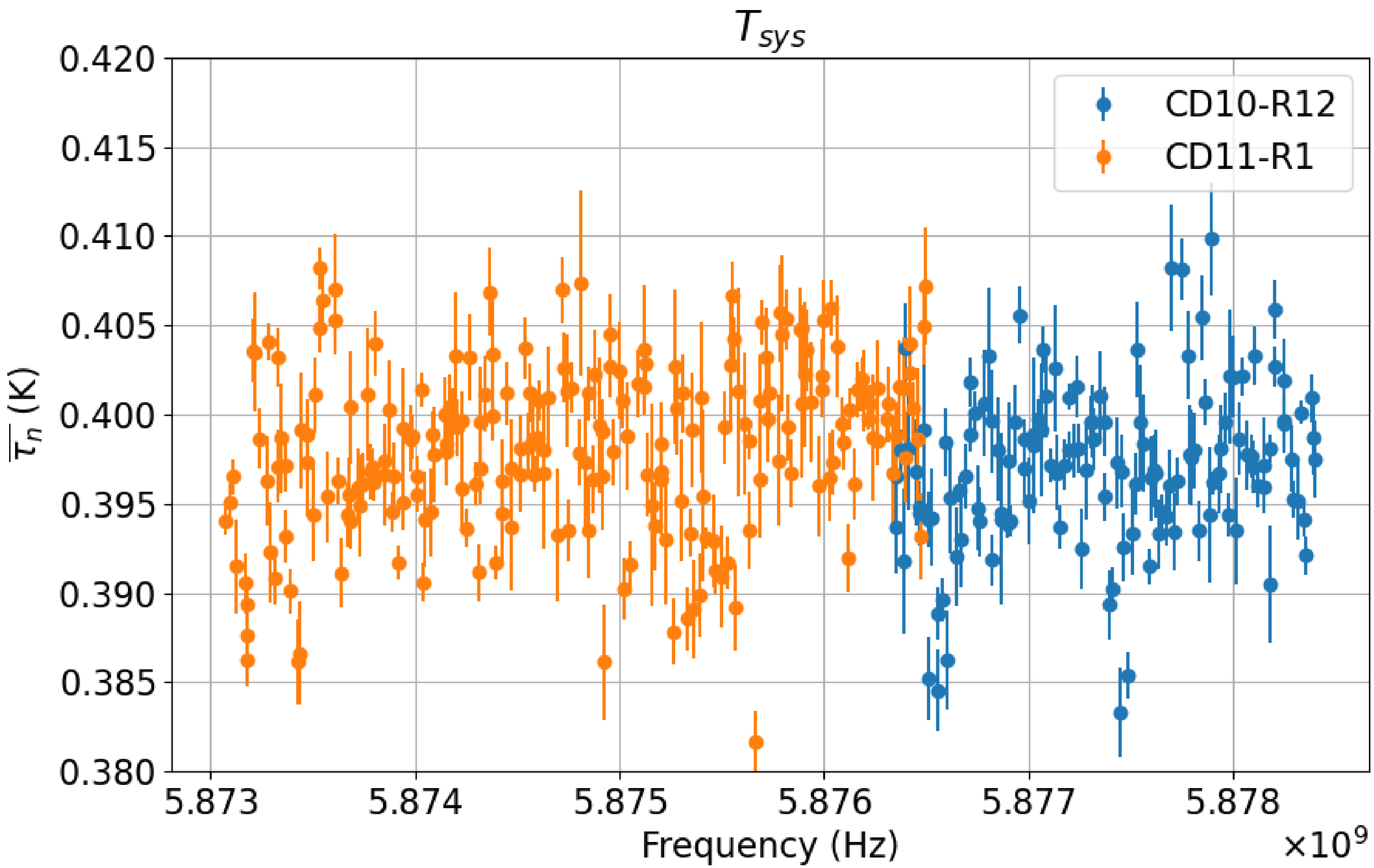
Extra: System Noise Temperature Repeatability



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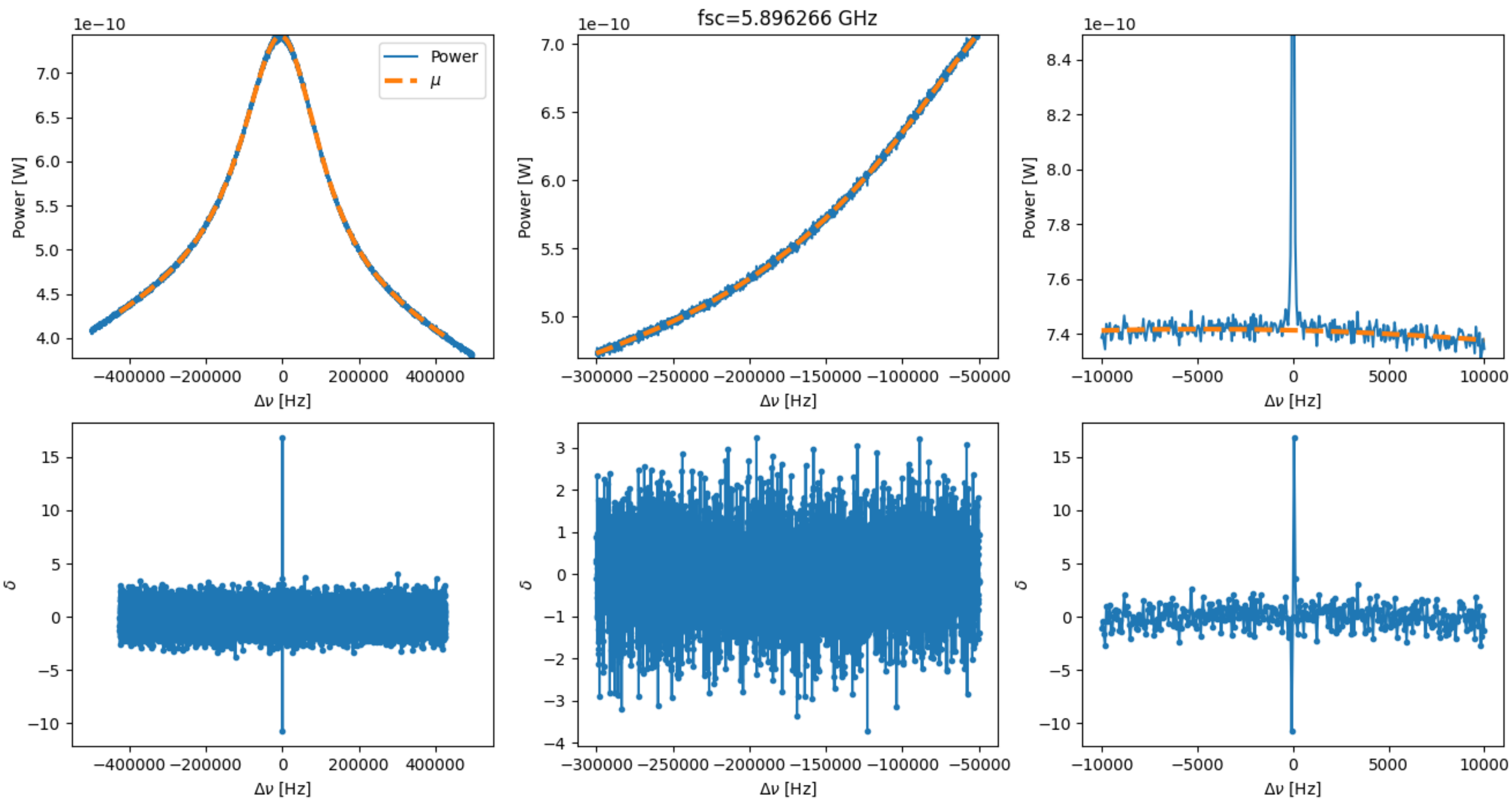
Extra: Example Baseline Extraction



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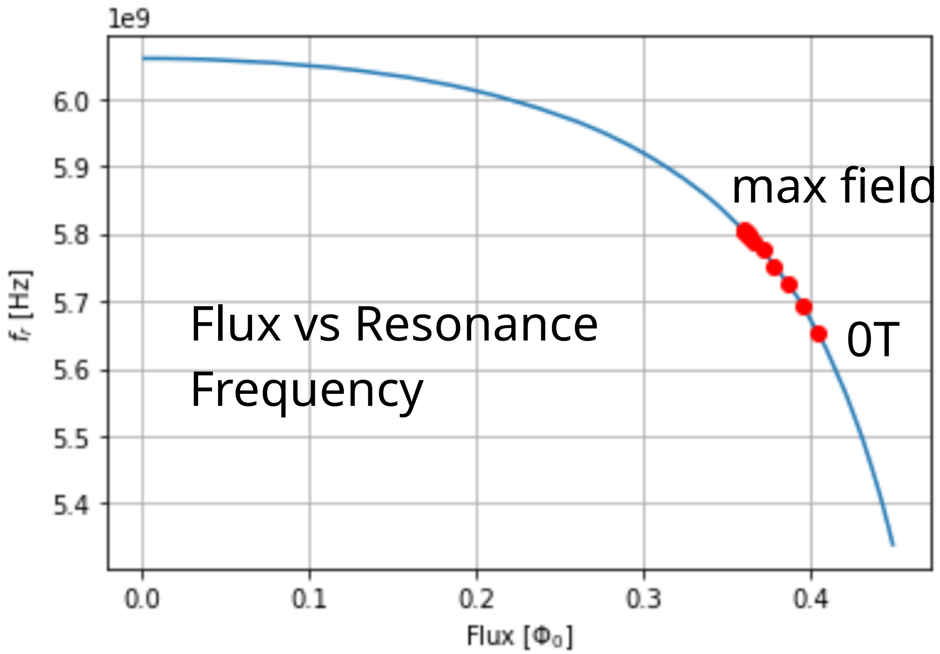
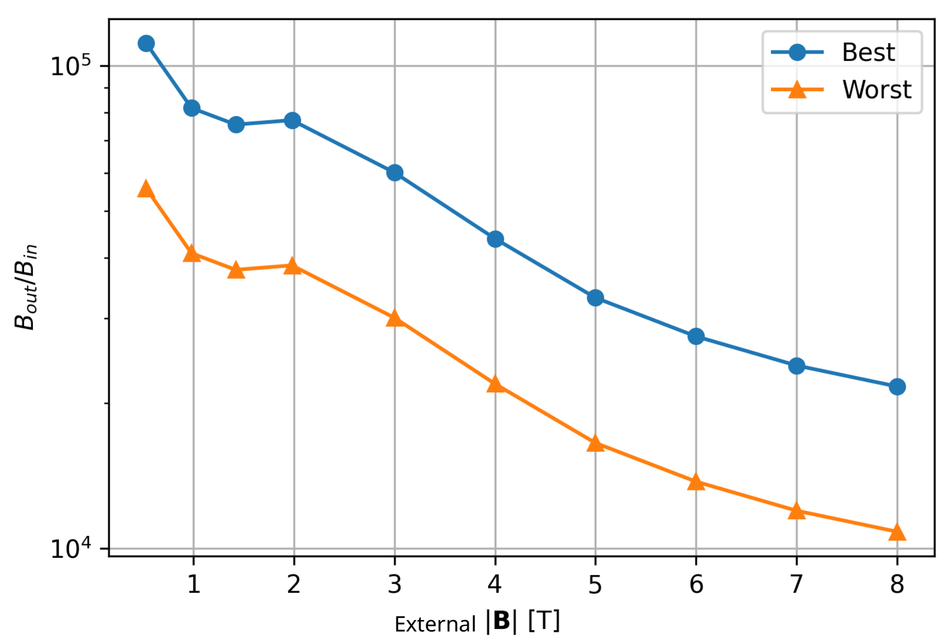
Extra: Magnetic shielding factor for the JPA



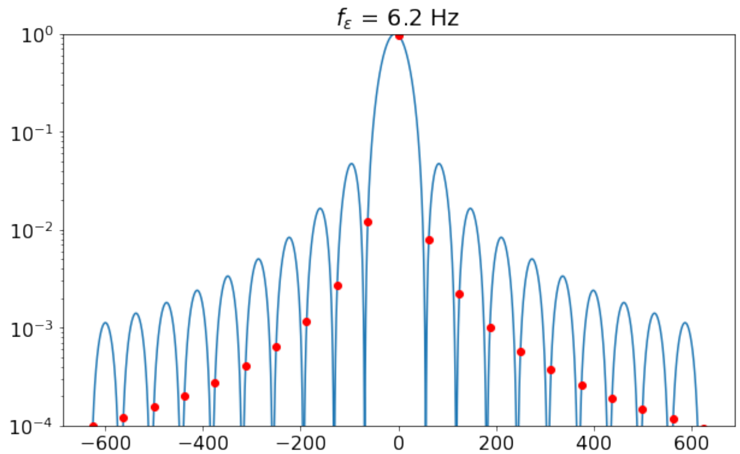
3-layered shield, from inner to outer:
- Aluminum
- μMetal
- Nb

At highest field, field penetration measured corresponds to a 0.05 of a flux quantum passing through the SQUID loop within JPA.

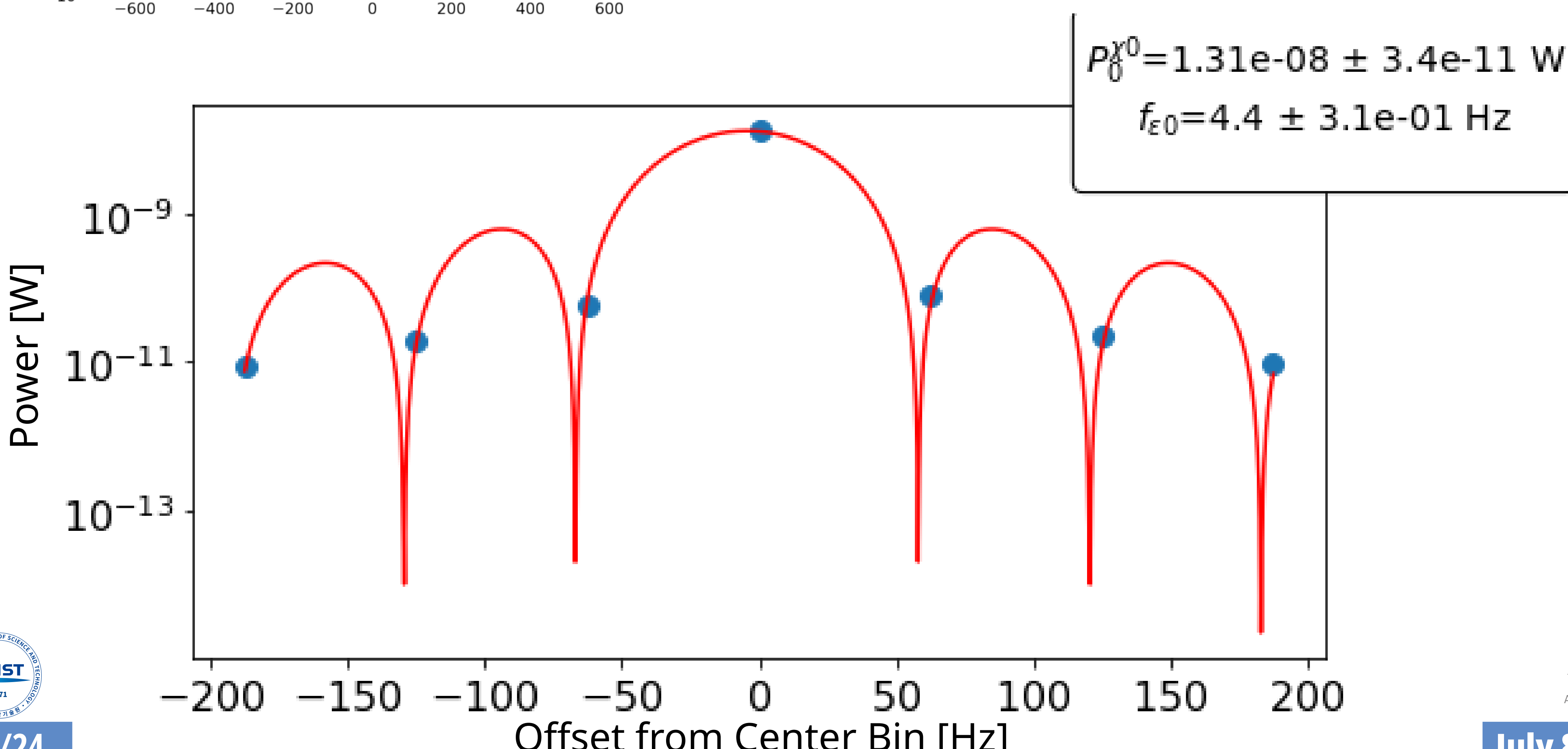
Shielding factor is estimated from shifts of resonance frequency with respect to magnetic field, where the field at the JPA position is taken from B-field simulations.



Extra: Excess due to pump downmixing



- Observation of a single tone in FD will have the shape of squared sinc function.
- One can obtain the amplitude and offset from a fit.



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