Dark Matter Axion Search
Using an 18T HTS Magnet Haloscope

Jonghee Yoo
Seoul National University

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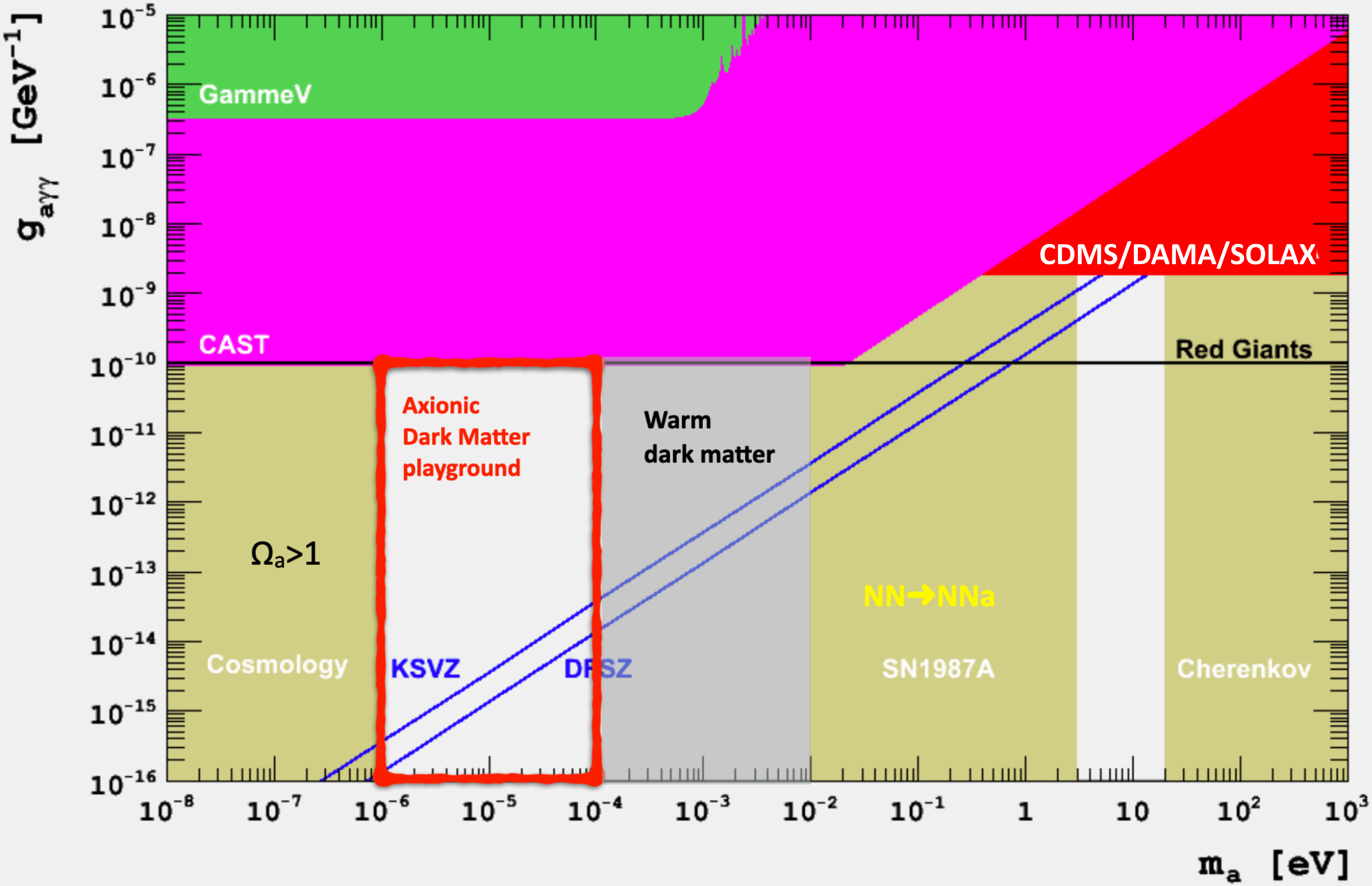
UCLADM

Axion Dark Matter



Axion Dark Matter Search in A Nutshell

Assume: $m_a \simeq \mu\text{eV}$

$$\rho_{DM} = 3\times 10^{8}\,\text{eV/cc} = 2.4\times 10^{-6}\text{eV}^4$$

$$\beta = 10^{-3} \text{ or } < v_a >= 10^{-3}c$$

$$L_{coh} = \frac{1}{p} \simeq 10^{9}\text{eV}^{-1} \simeq 200\,\text{m}$$

$$t_{coh} = \frac{1}{E} \simeq 10^{12}\text{eV}^{-1} \simeq \text{msec}$$

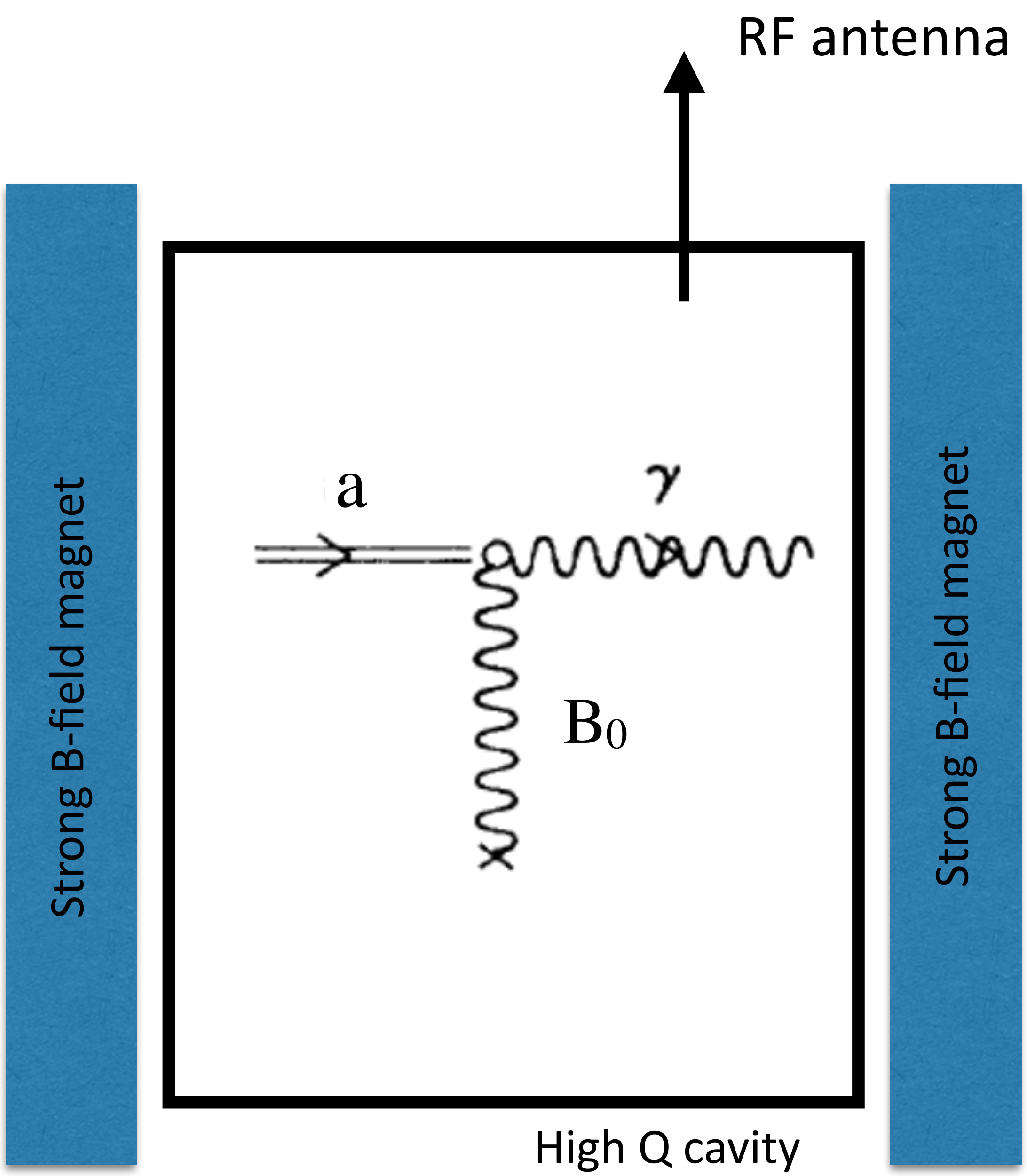
$$\mathcal{L} \equiv -\frac{1}{4} g a F\tilde{F} \approx \frac{\alpha}{8\pi f_{PQ}} a F\tilde{F}$$

$$= g a \vec{E}\cdot\vec{B}$$

$$\frac{\partial(\mathbf{E}^2/2)}{\partial t} - \mathbf{E}\cdot(\nabla\times\mathbf{B}) = g_{a\gamma}\dot{a}(\mathbf{E}\cdot\mathbf{B})$$

Oscillating source current ➜ RF photons

RF photon frequency = axion mass

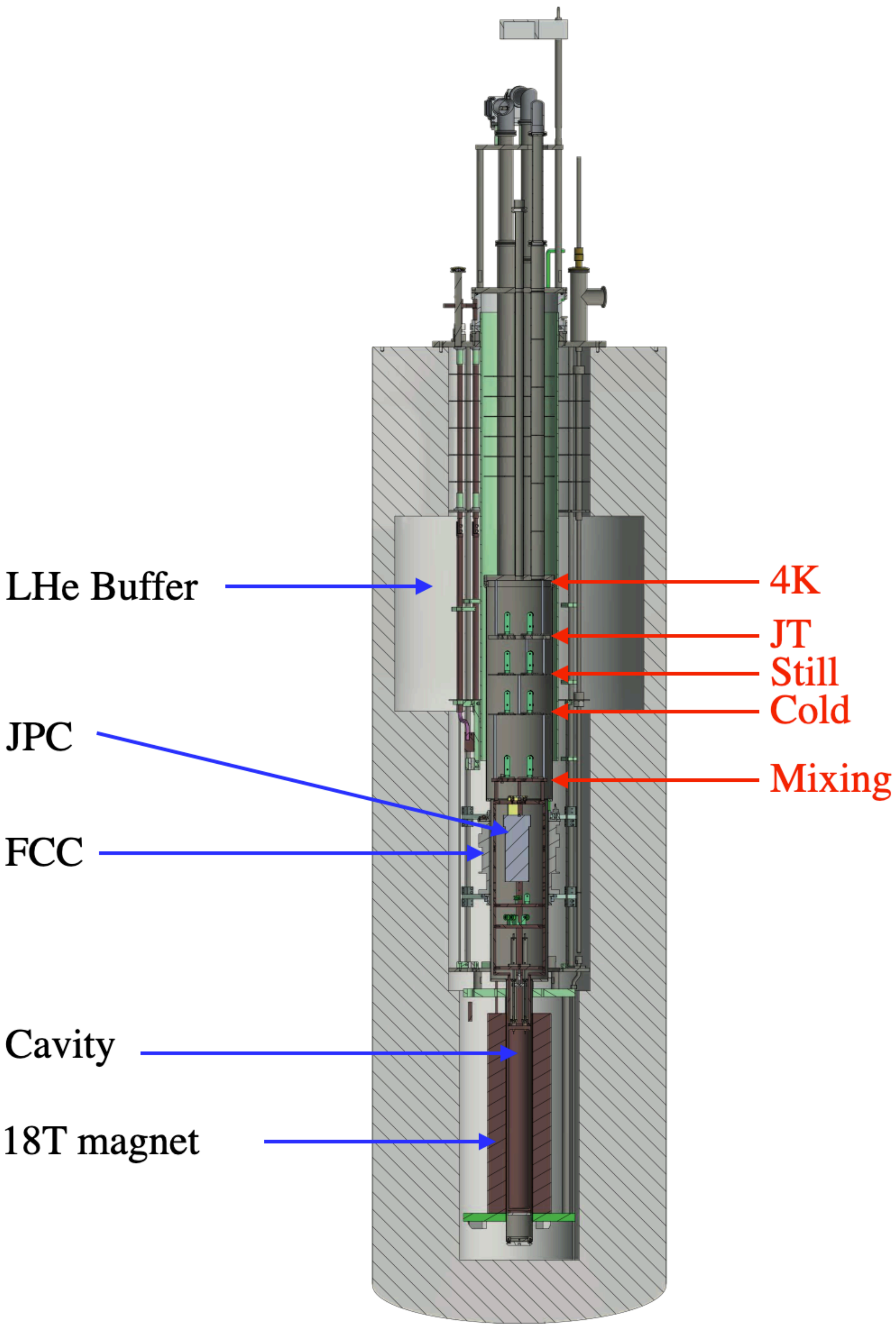


$$P_a = g^2 \frac{\rho_a}{m_a} B_0^2 V \times \min(Q_{\text{cav}}, Q_a)$$

~ 10^{-21}W at m_a=μeV

(assuming B=8T, V=0.2 m^3 magnet and cavity Q =10^5)

Dark Matter Axion Search Strategy



Axion Frequency Scan Speed

Strong magnetic field (18T)

Increase cavity volume?

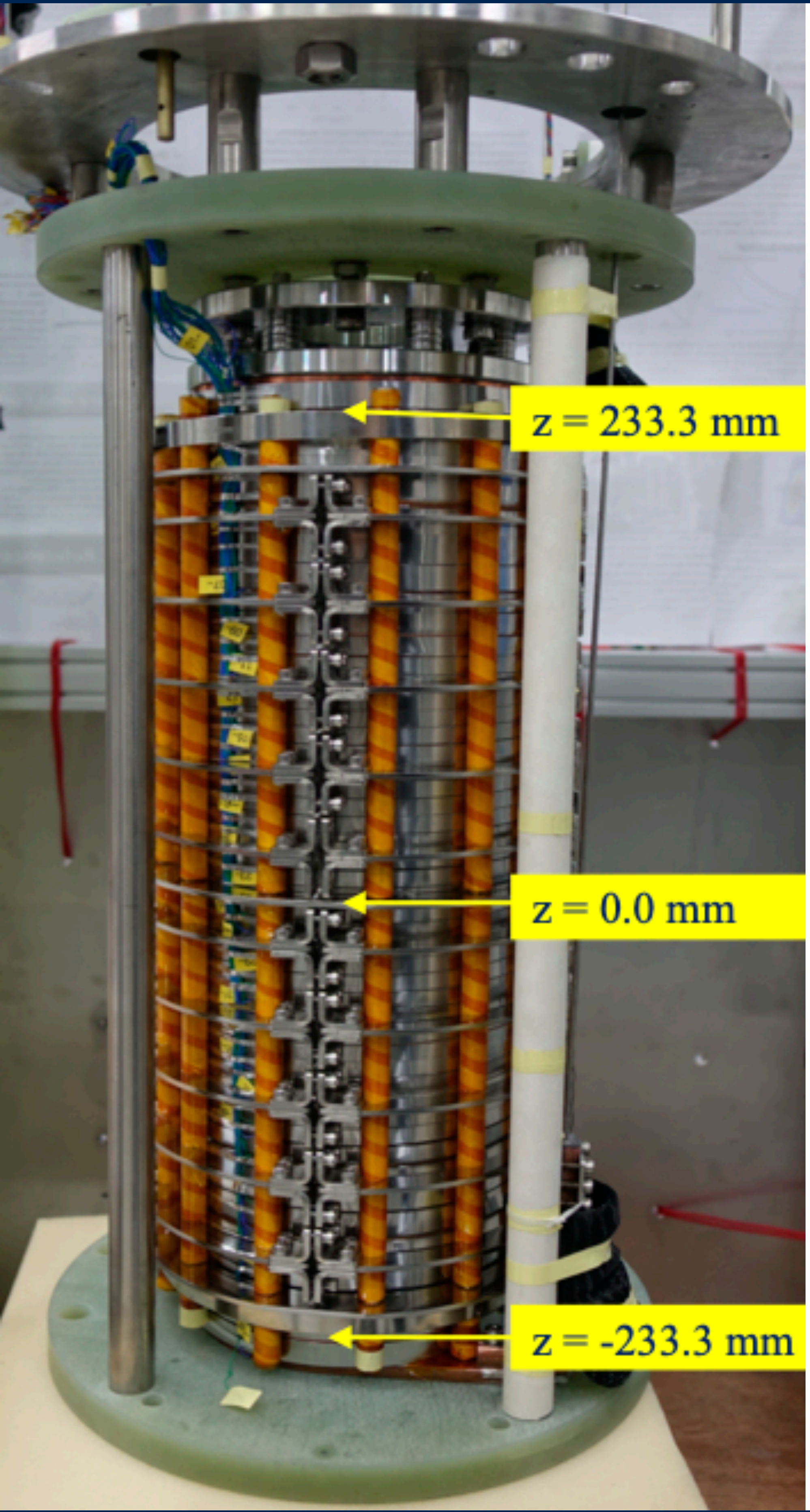
High Q cavity

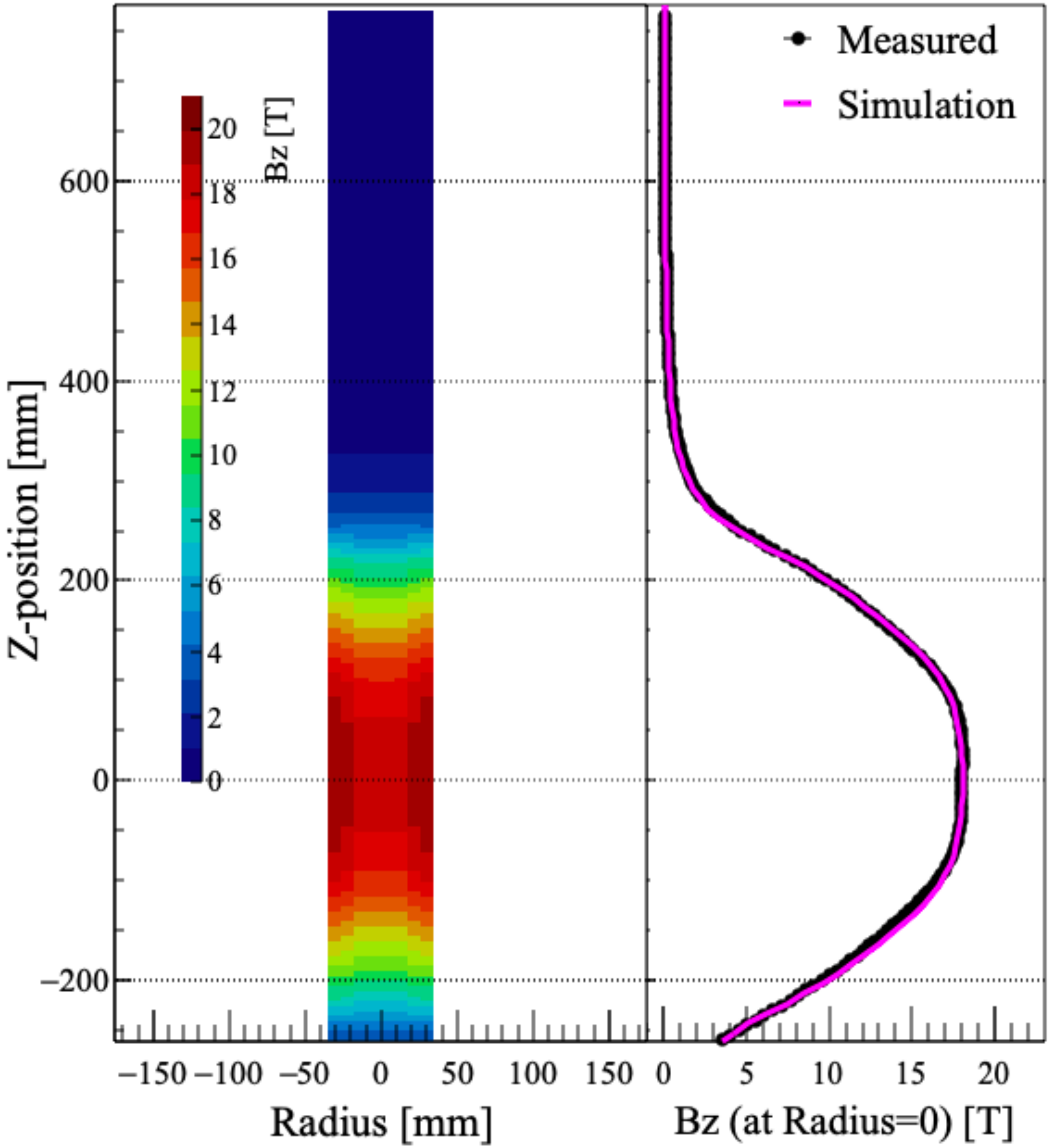
$$\frac{d\nu_a}{dt} \propto g_a \nu_a^2 \rho_{DM} C^2 Q \frac{V^2 B^4}{T^2}$$

Cavity form factor

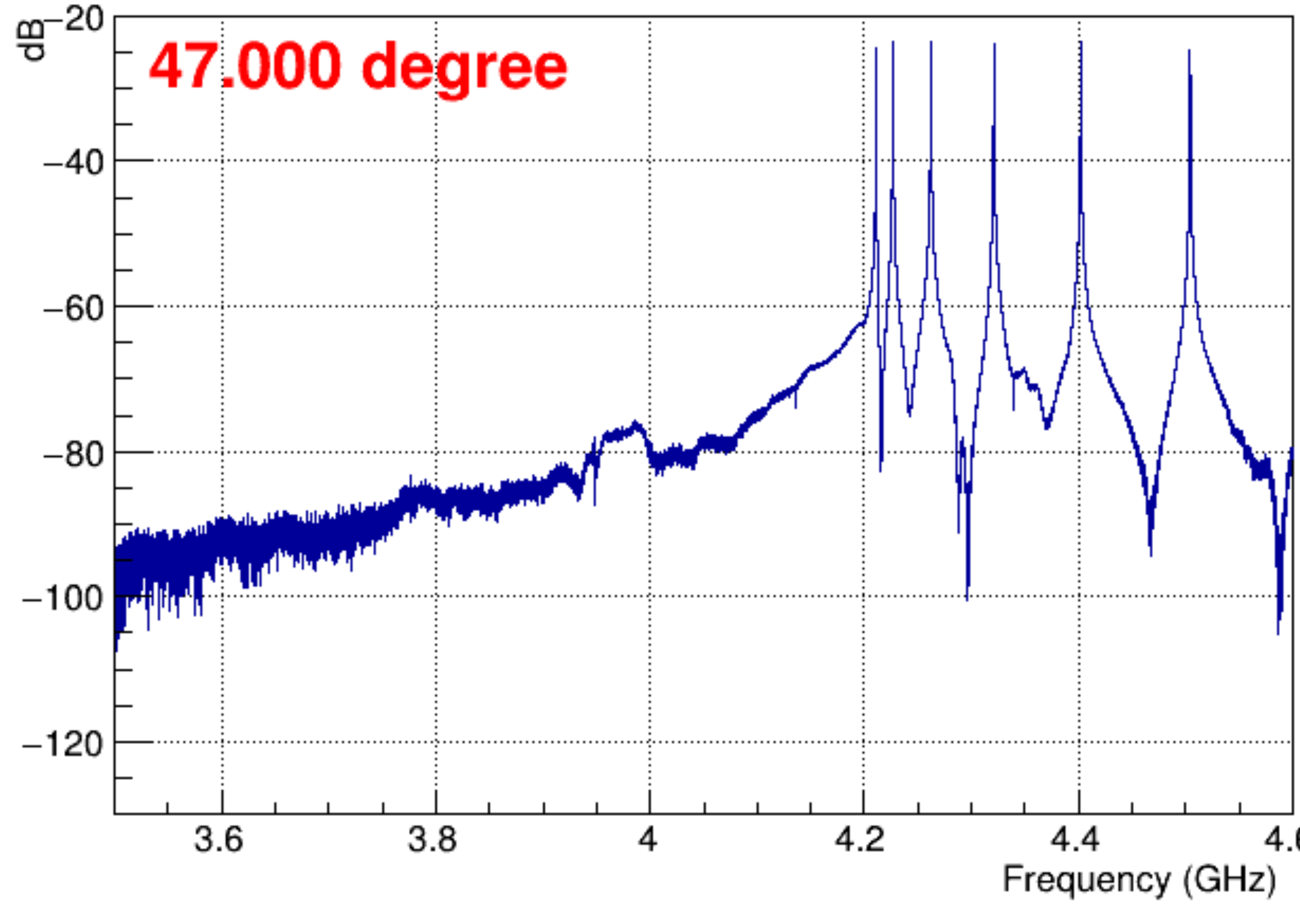
Lower the noise temperature

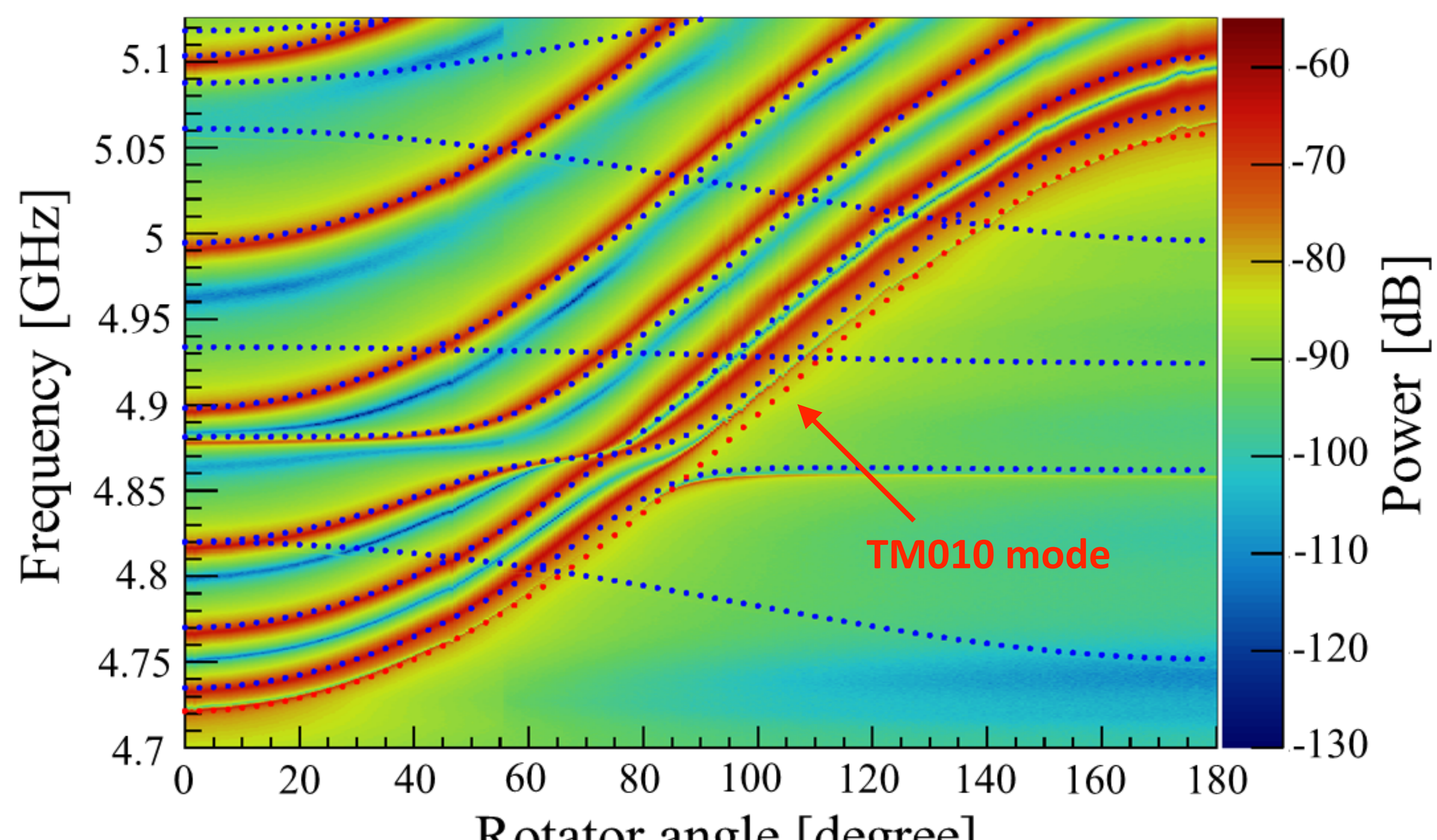
18T HTS Magnet



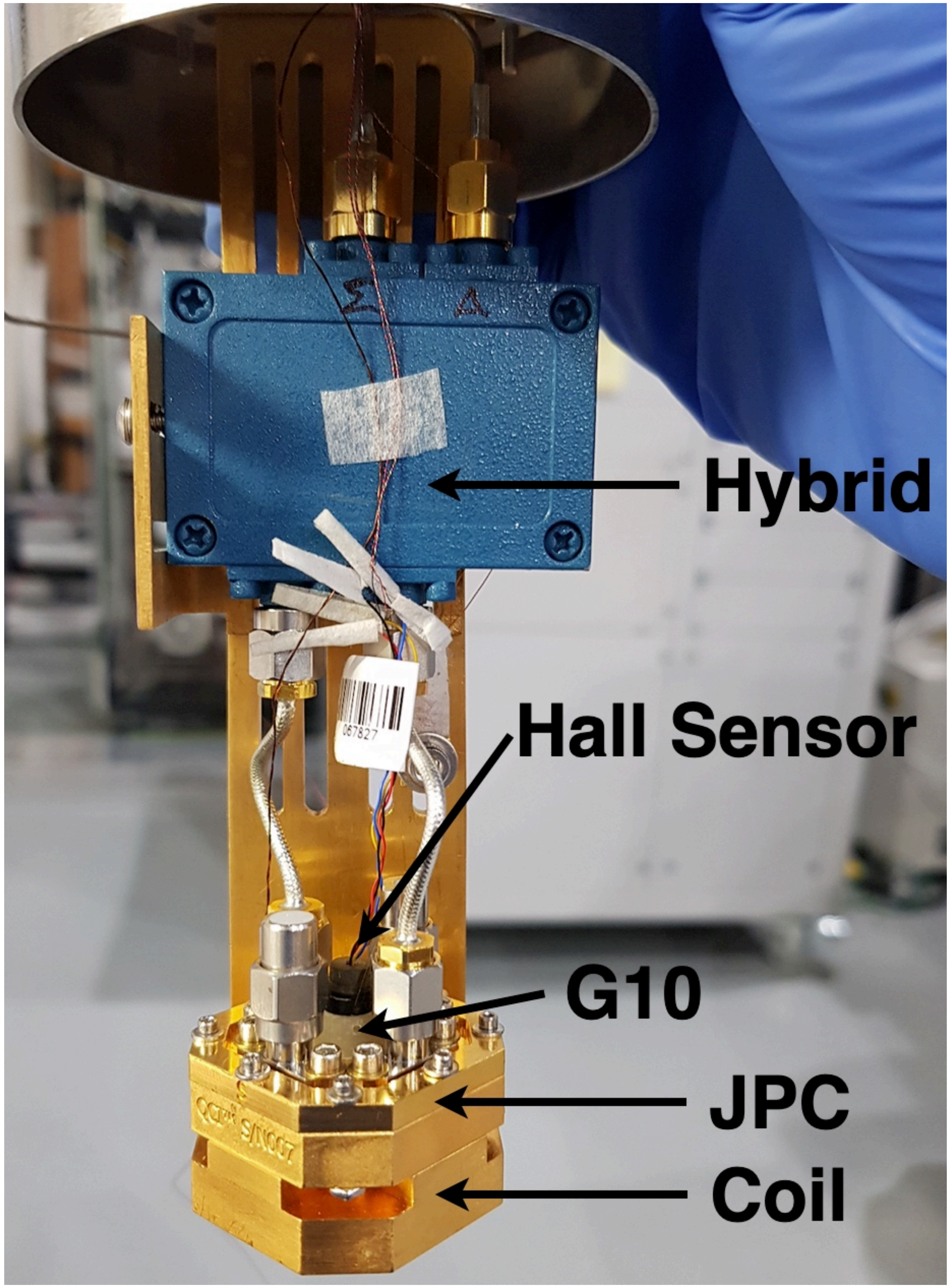


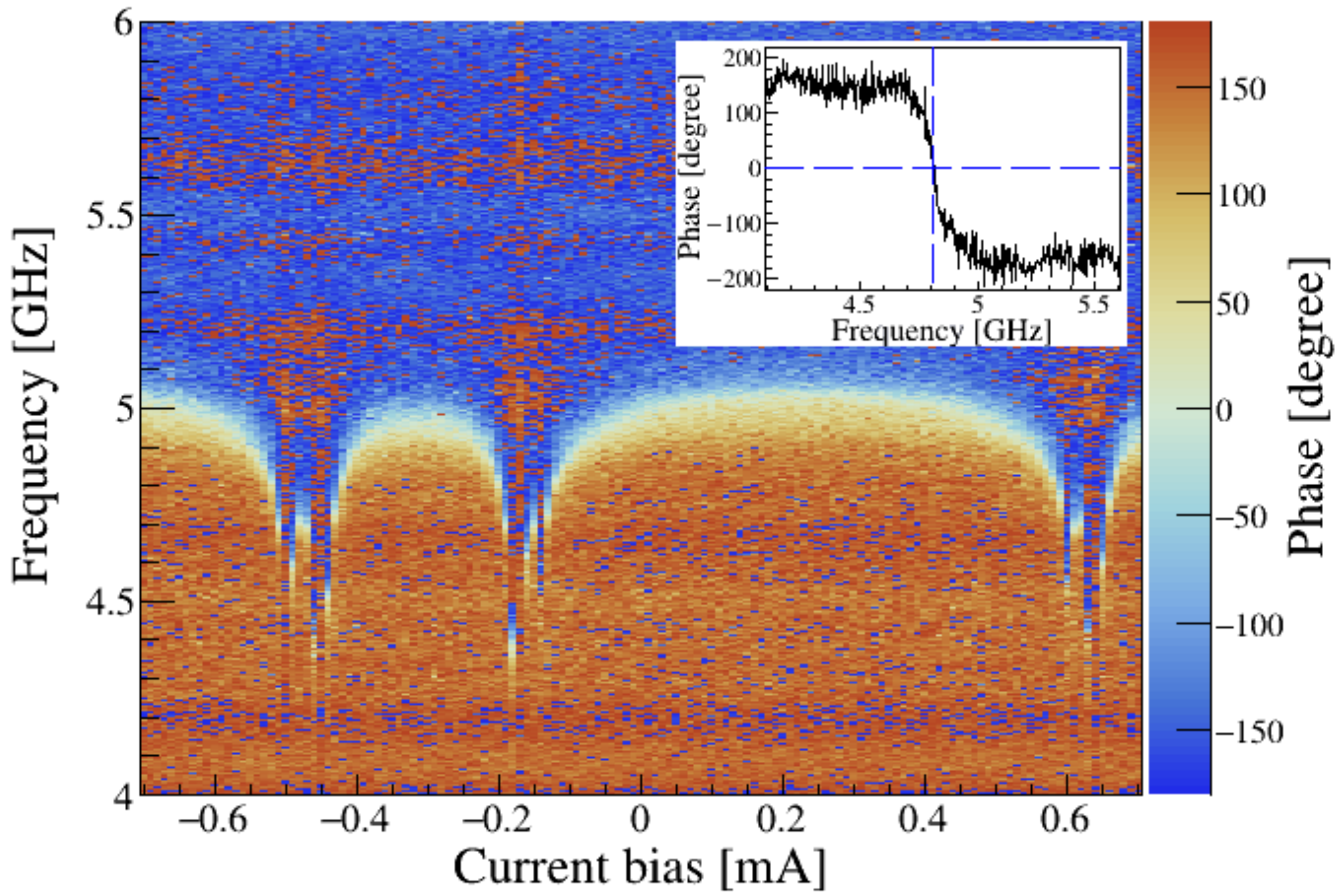
Cavity: Frequency Tuning

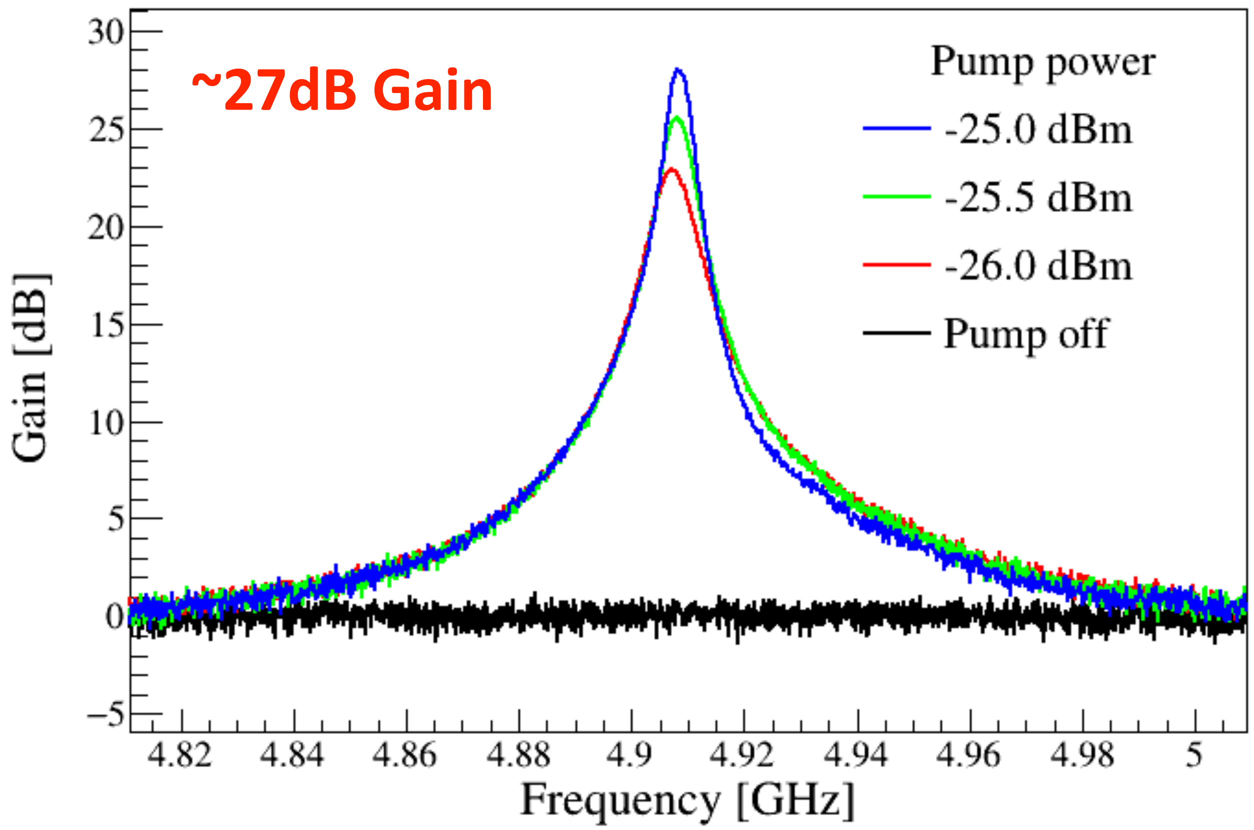




Quantum Amplifier: Josephson Parametric Converter



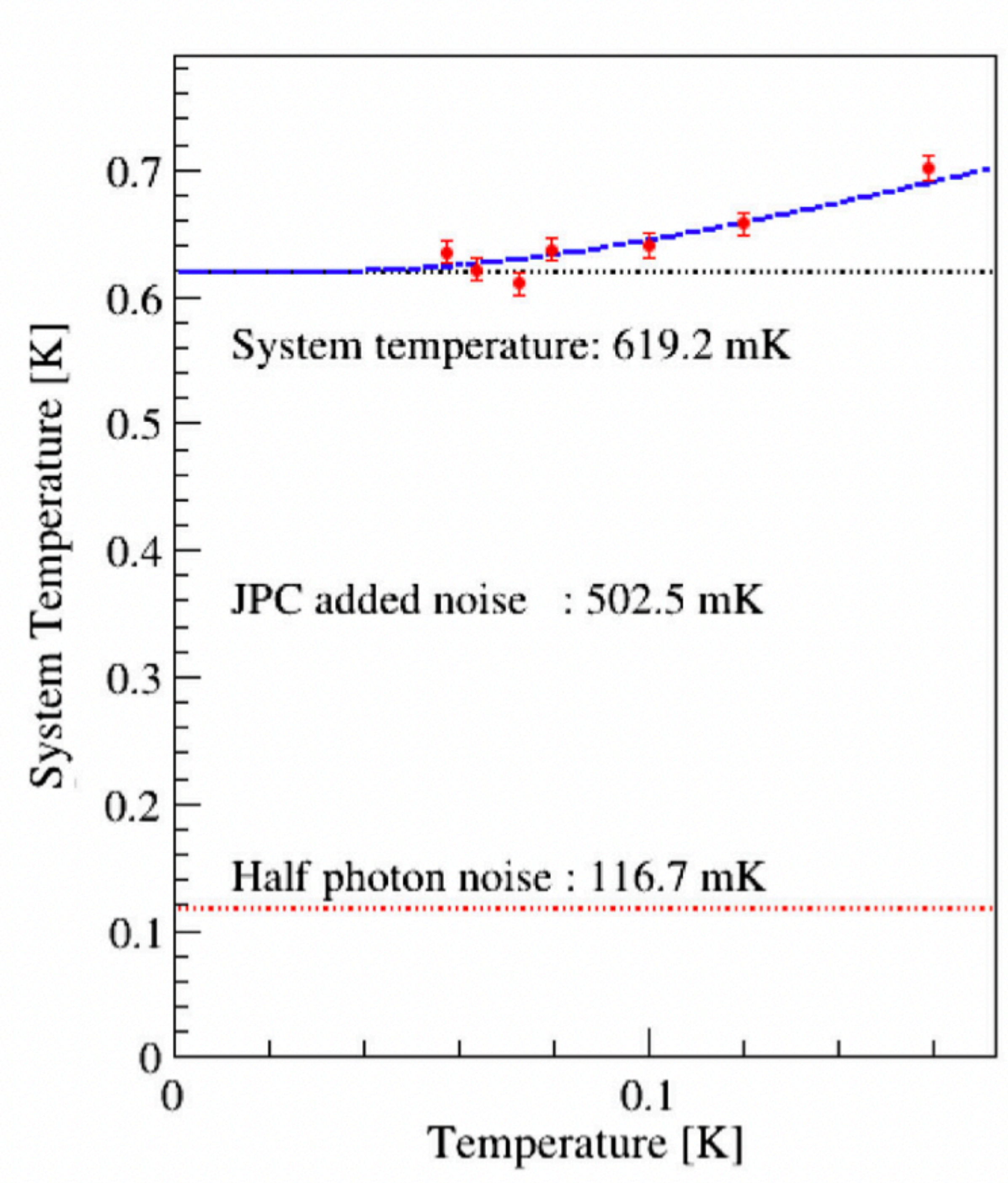


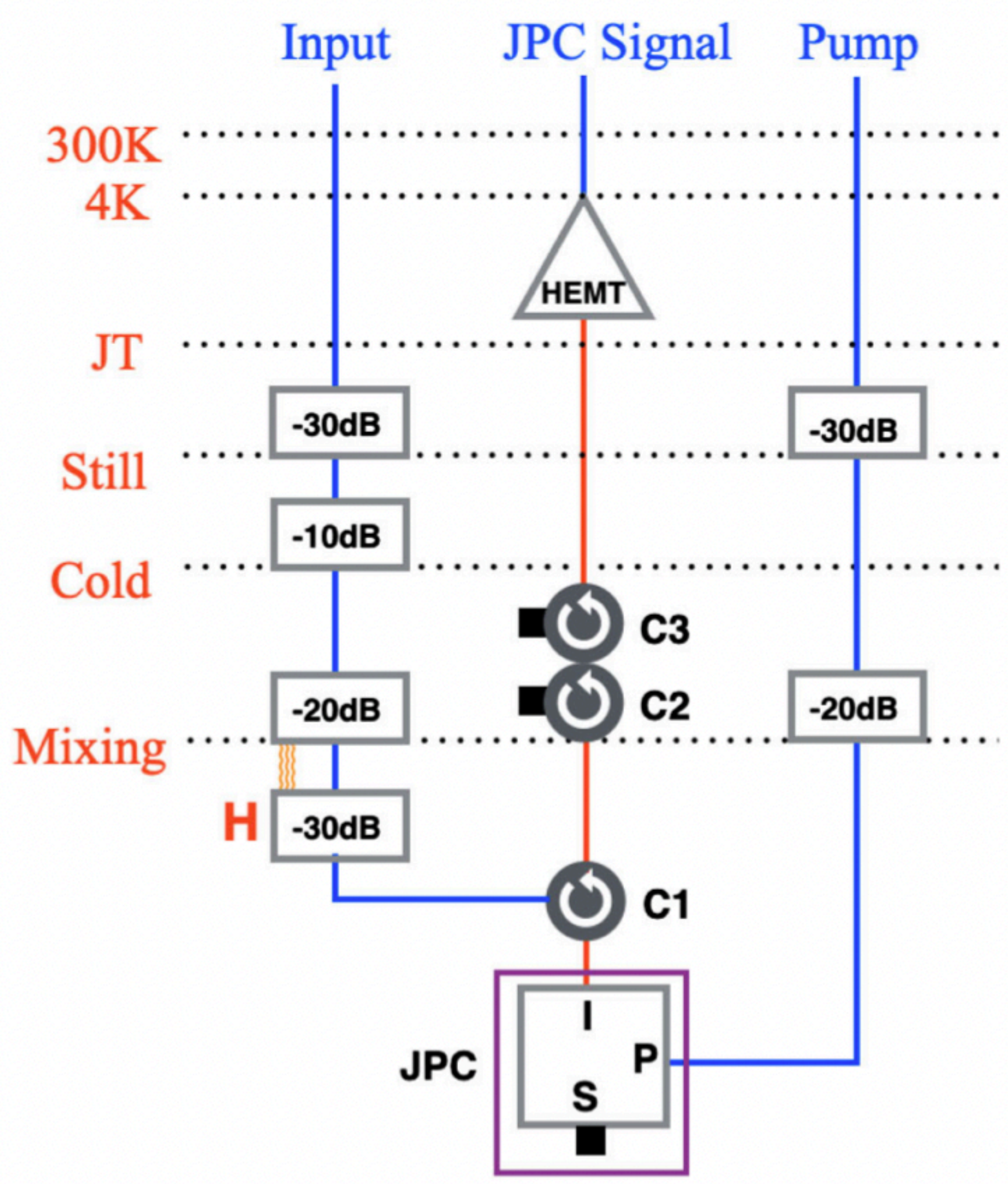


JPC Noise Temperature

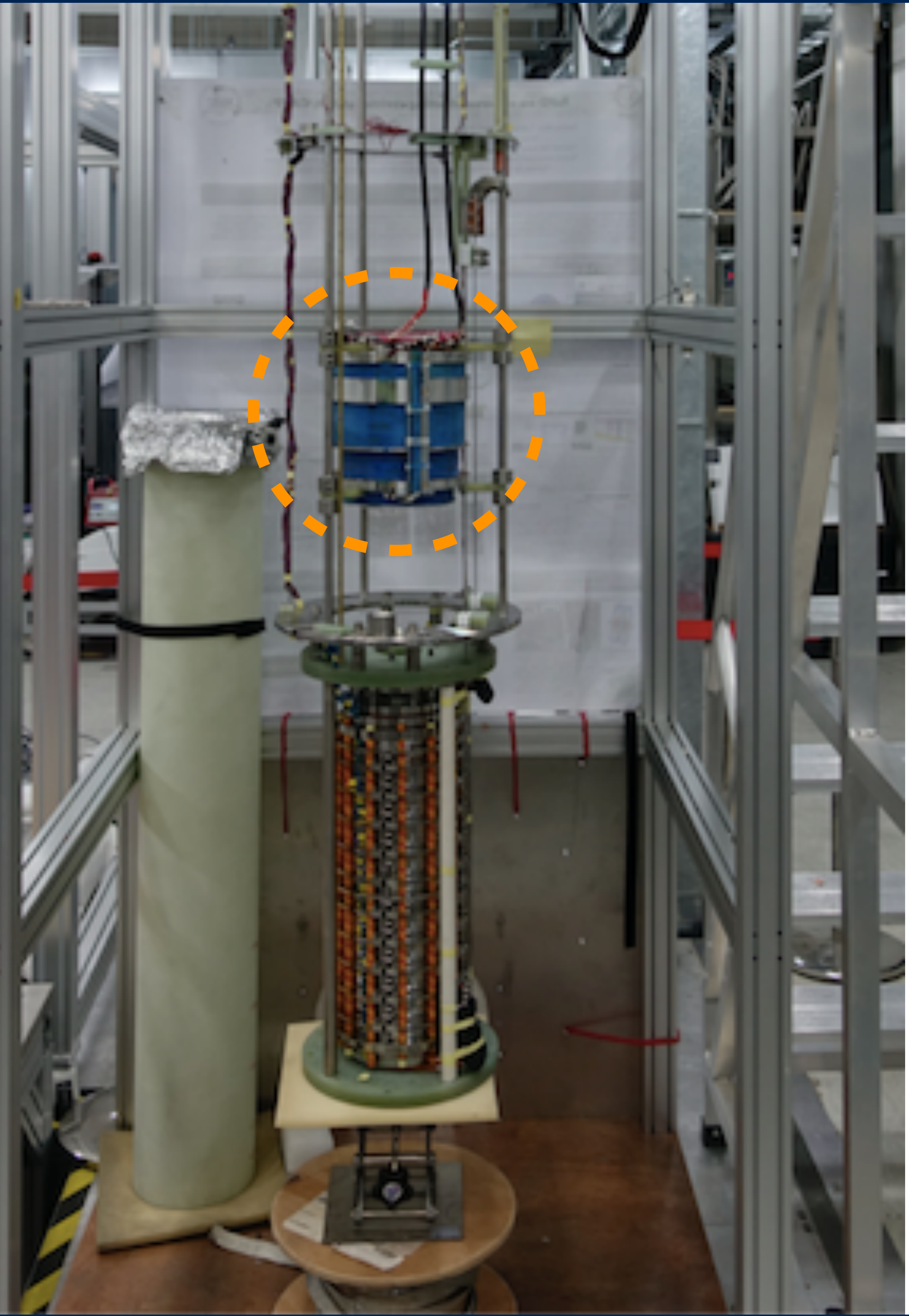
$$\frac{d\nu_a}{dt} \propto g_a \nu_a^2 \rho_{DM} C^2 Q \frac{V^2 B^4}{T^2}$$

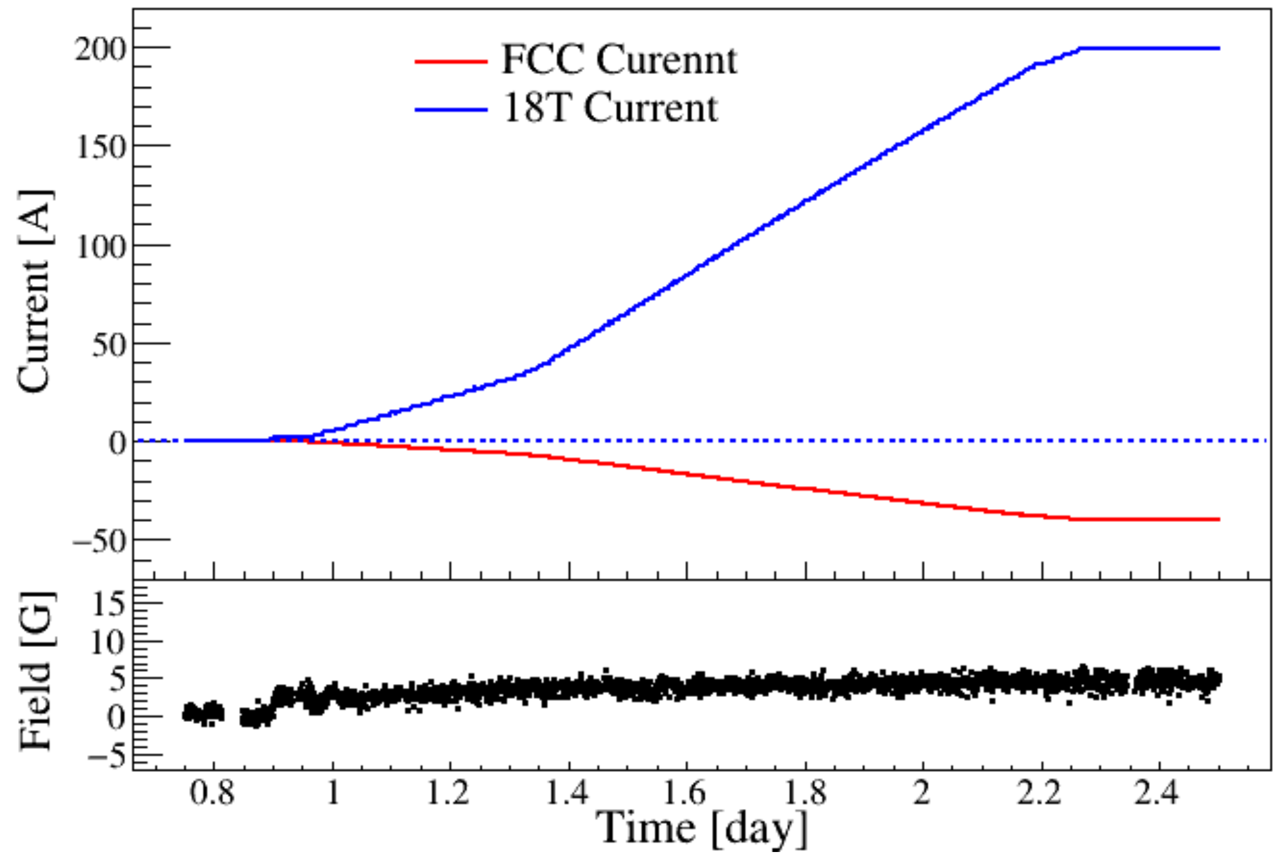
$$T_{sys} = T_P + T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \ldots$$

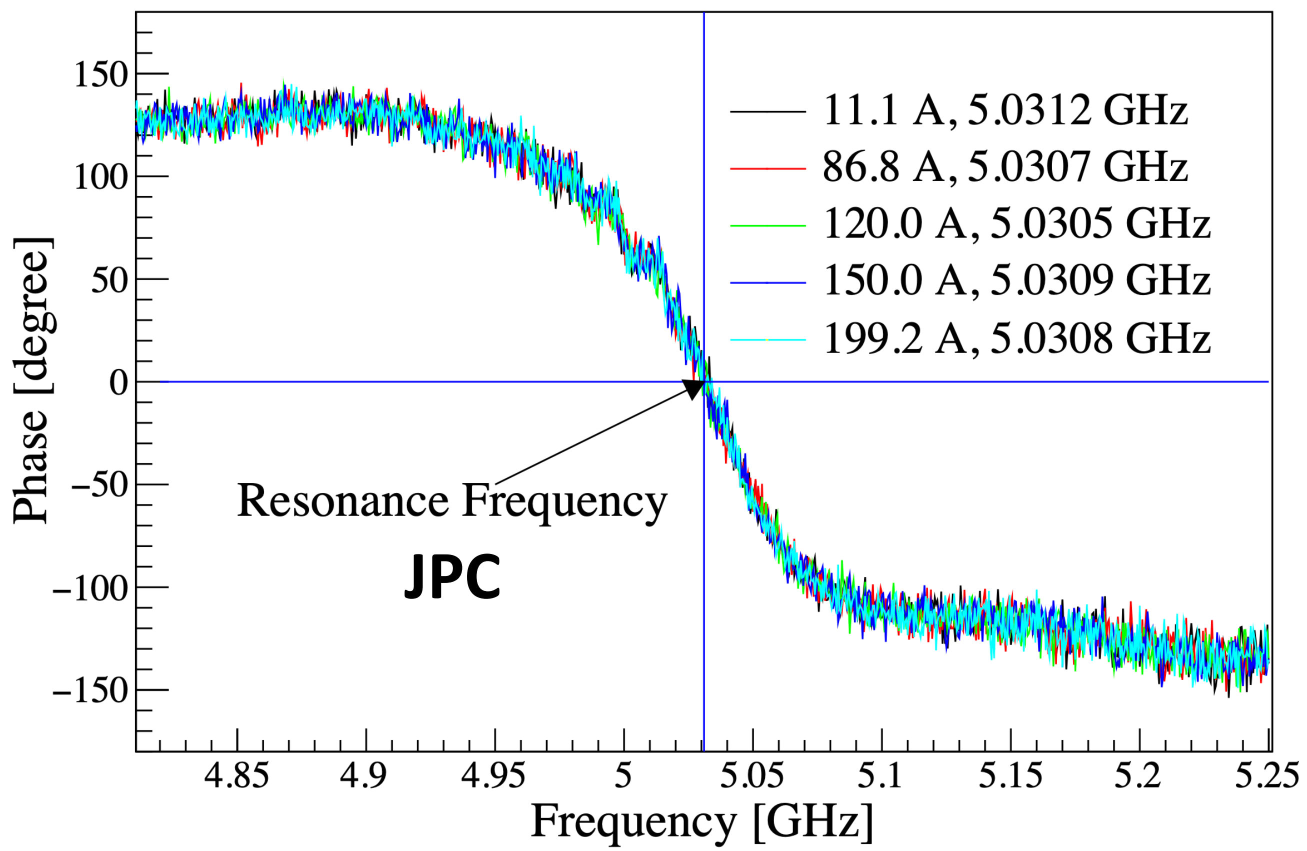




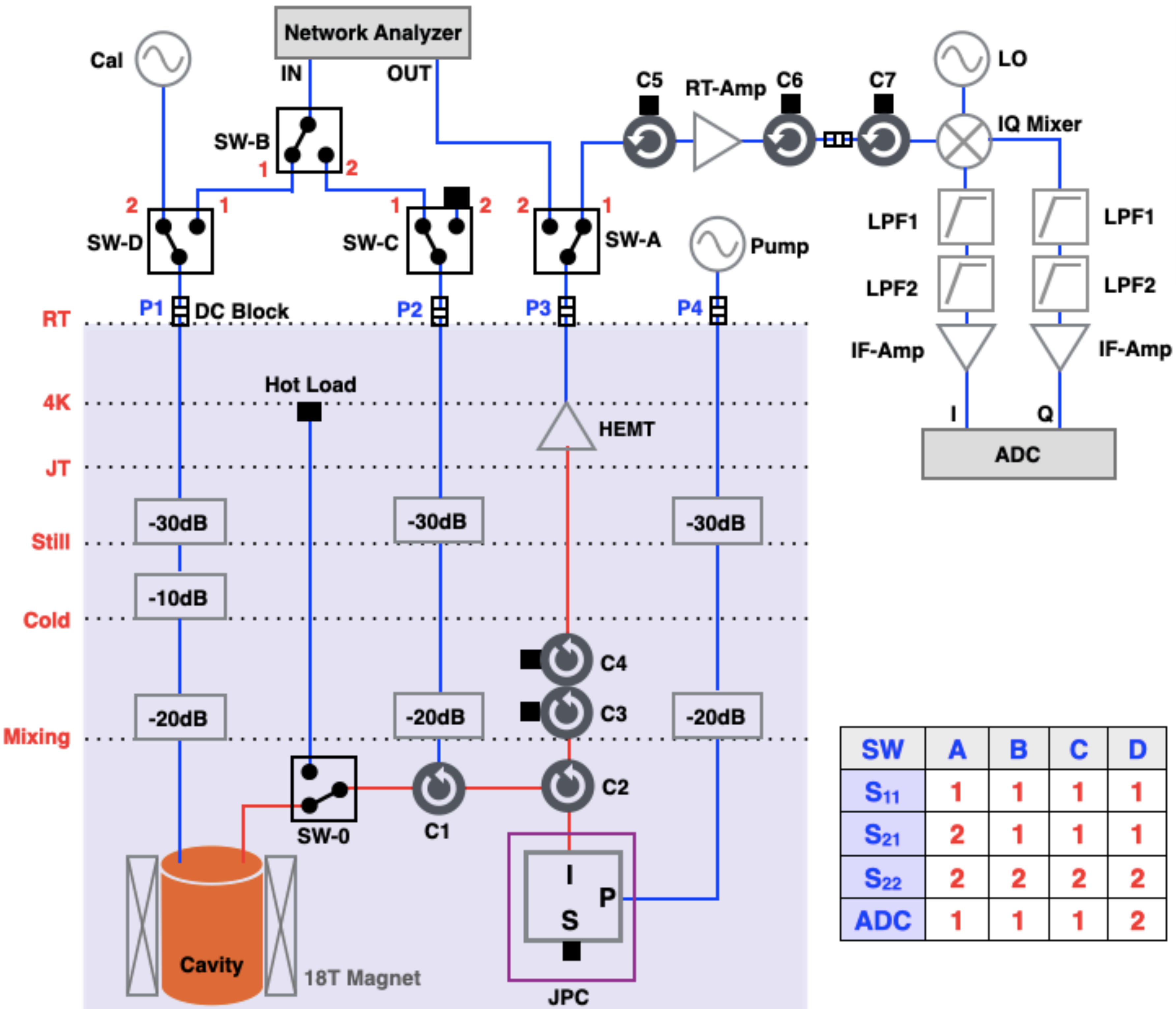
Field Cancellation and JPC Response



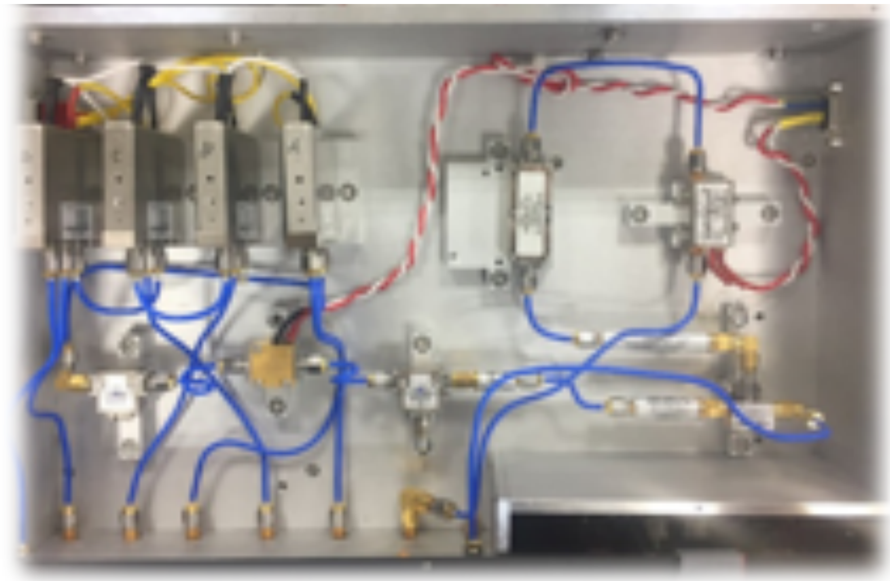


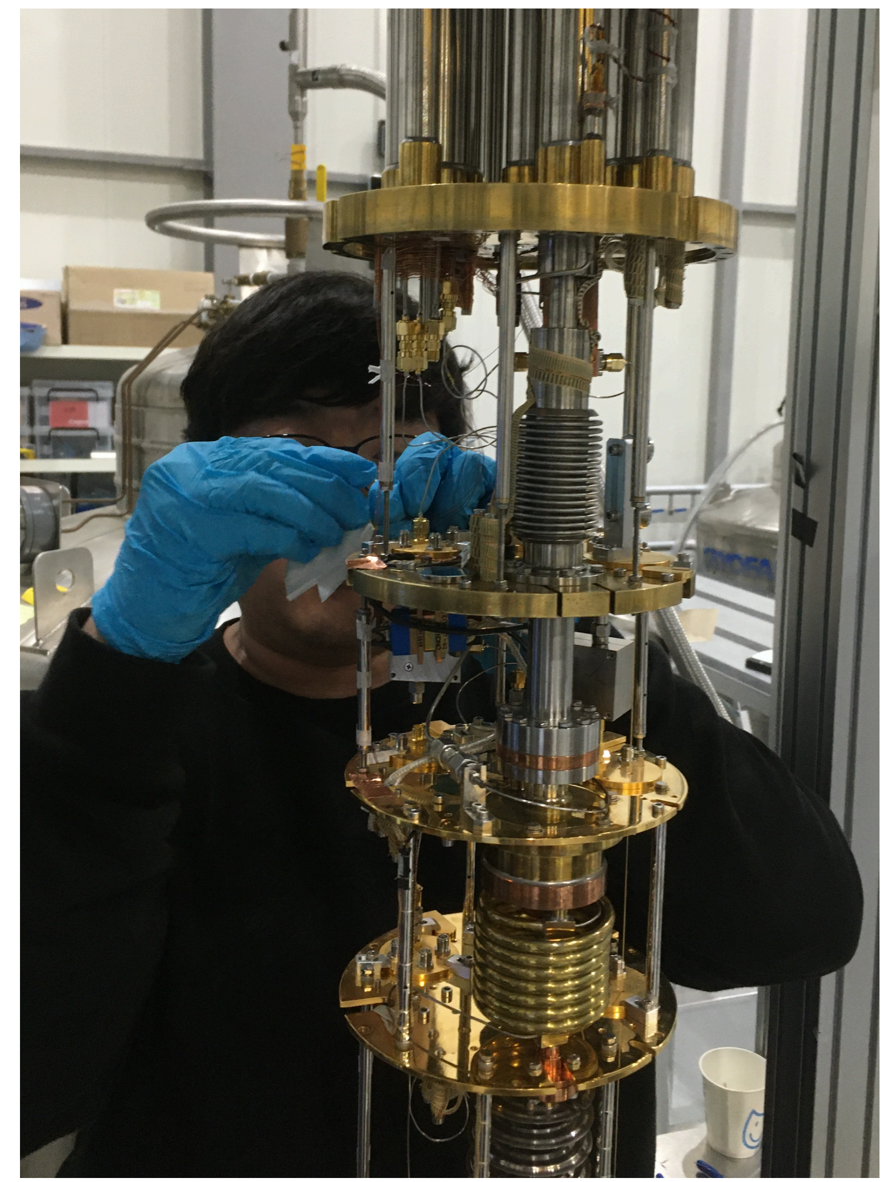


RF Chain

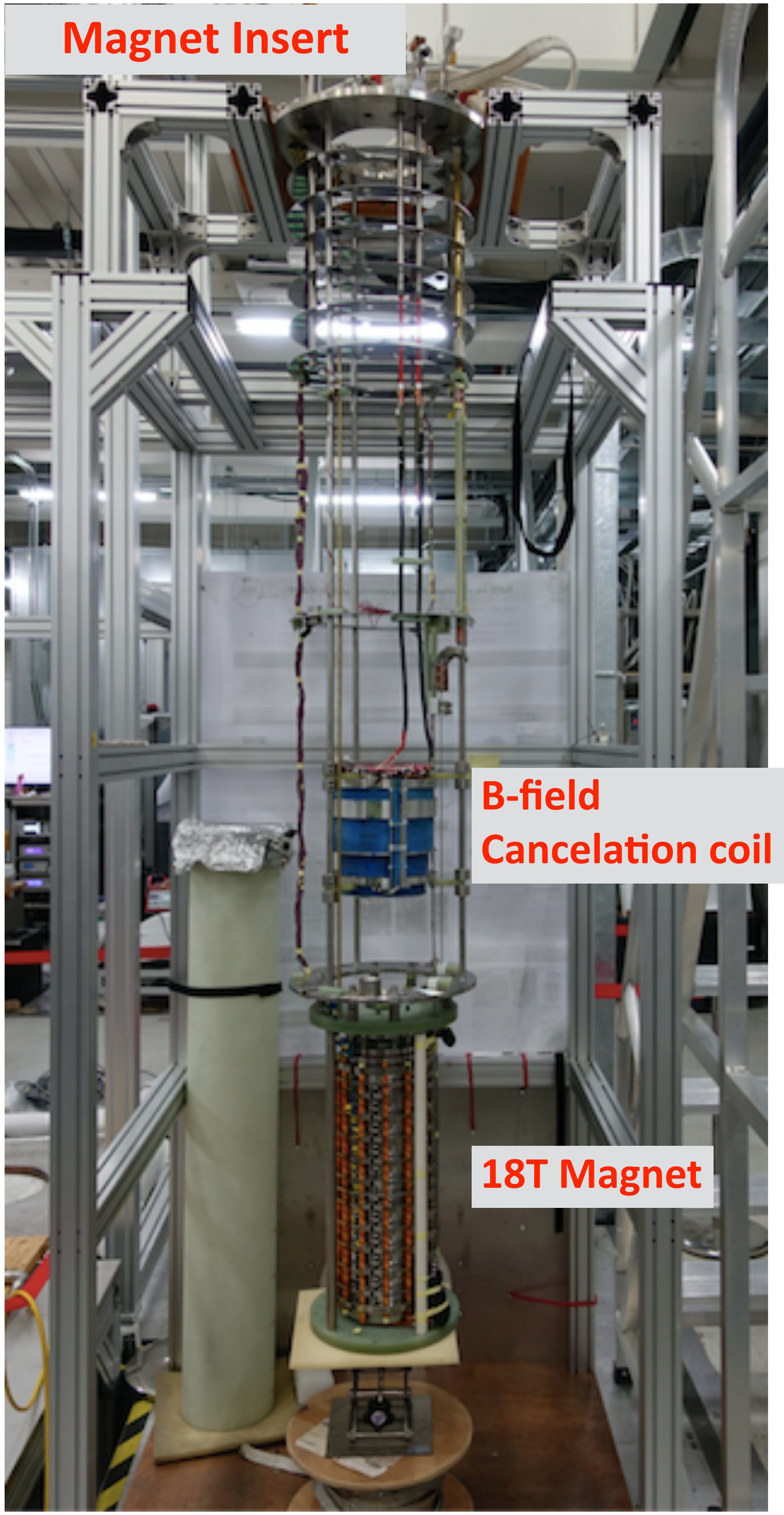


SW	A	B	C	D
S_{11}	1	1	1	1
S_{21}	2	1	1	1
S_{22}	2	2	2	2
ADC	1	1	1	2

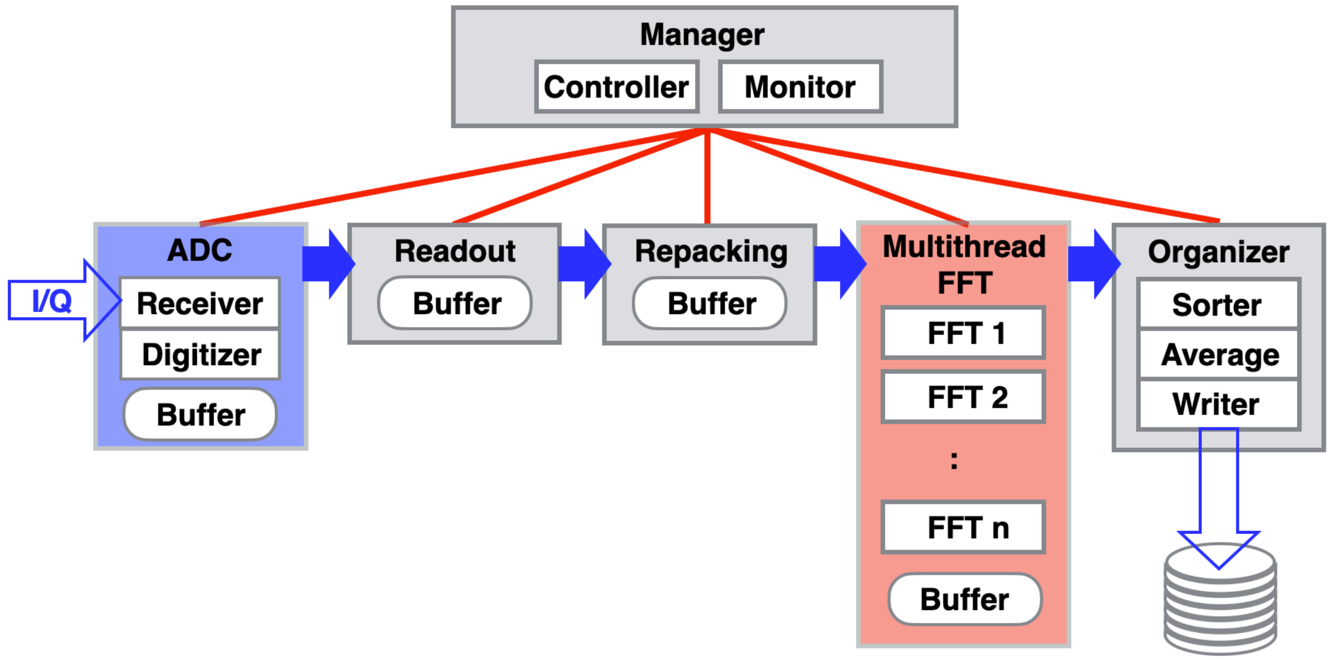




Full System Assembly

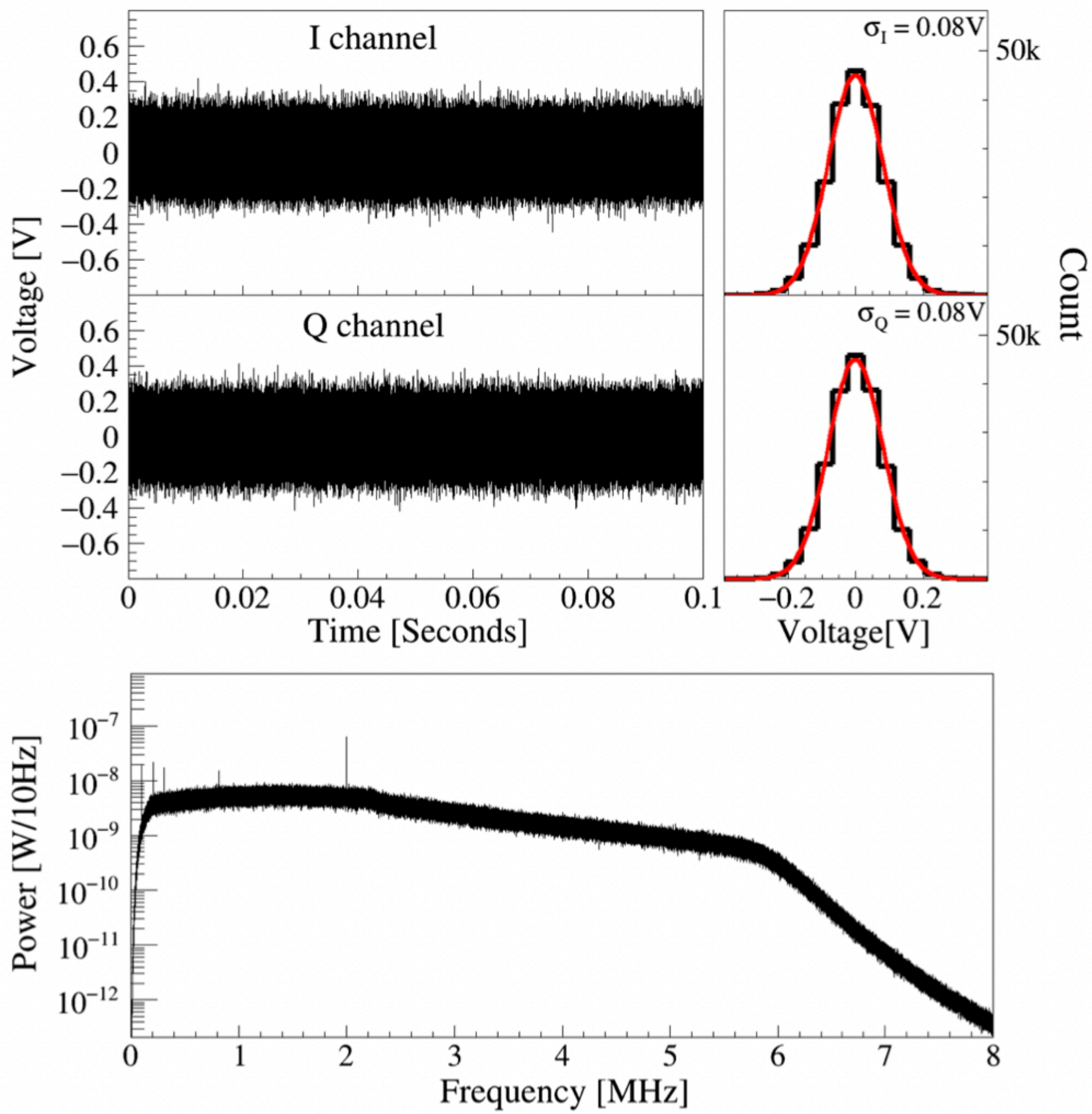


Deadtime Free DAQ



- Realtime multithread FFT
- 80MS/s data stream without buffer fill

→ **100% DAQ livetime achieved!**



- ADC module: Signatech PX14400A
- 14bit (400 MS/s), 2-ch
- Infinite sampling mode

Axion Dark Matter Search

Detector Commissioning: Apr.~ Nov. 2020
Dark Matter Search: 30 Nov. ~ 24 Dec. 2020
LHe consumption ~140L/day

Data Selection and Systematic Uncertainties

Net Detector Livetime

Selection criteria	Exposure (s)	([days])	Efficiency
After preselection	1 116 404.4	(12.9)	1.000
After anomalous SNRI cut	1 063 957.5	(12.3)	0.953
After ν_C drift cut	1 060 688.8	(12.3)	0.997
After Q_L fluctuation cut	1 047 782.9	(12.1)	0.988
2020 net sample	1 047 782.9	(12.1)	0.939
2021 net sample +	17 508.0	(0.2)	
Final sample	1 065 290.9	(12.3)	

Systematic Uncertainties

Source	Fractional uncertainty on P_a
B^2V	1.4%
$Q_L = Q_0/(1+\beta)$	0.5%
Coupling (β)	0.4%
Form factor (C_{010})	3.9%
T_S	8.5%
Total	9.5%

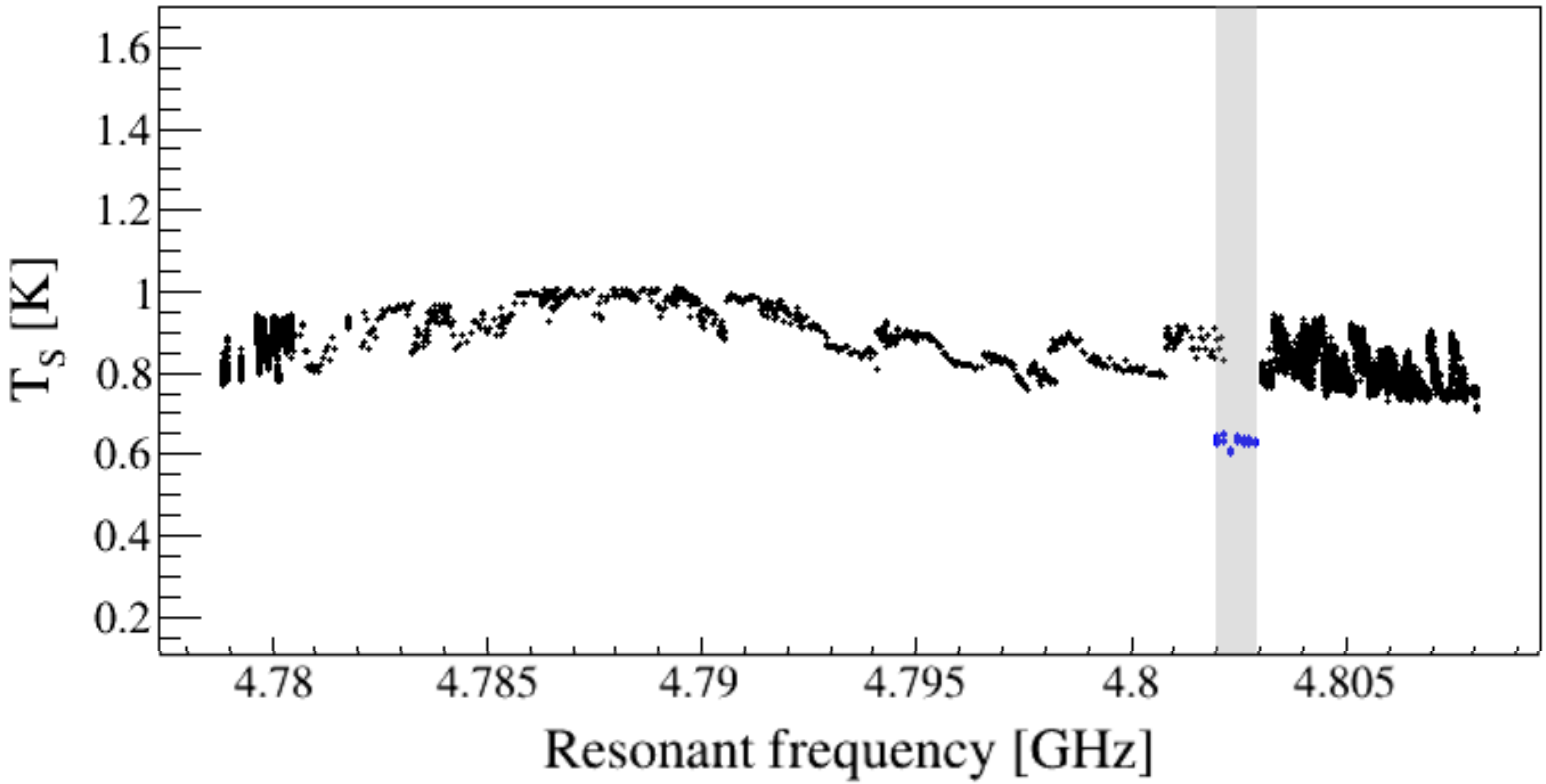
Axion Signal Power

$$P^a = g_{a\gamma\gamma}^2 \left(\frac{\rho_a}{m_a^2}\right) \omega_0 B_0^2 V C_{nlm} Q_0 \frac{\beta}{(1+\beta)^2}$$

Total System Noise Temperature

Signal to Noise Ratio Improvement (SNRI)

$$T_S = \left[\frac{P_{\rm on}/G_{\rm on}}{P_{\rm off}/G_{\rm off}}\right] T_R = \frac{T_R}{\rm SNRI} \qquad {\rm SNRI} \equiv (G_{\rm on} P_{\rm off})/(G_{\rm off} P_{\rm on})$$



Grand Power Spectrum

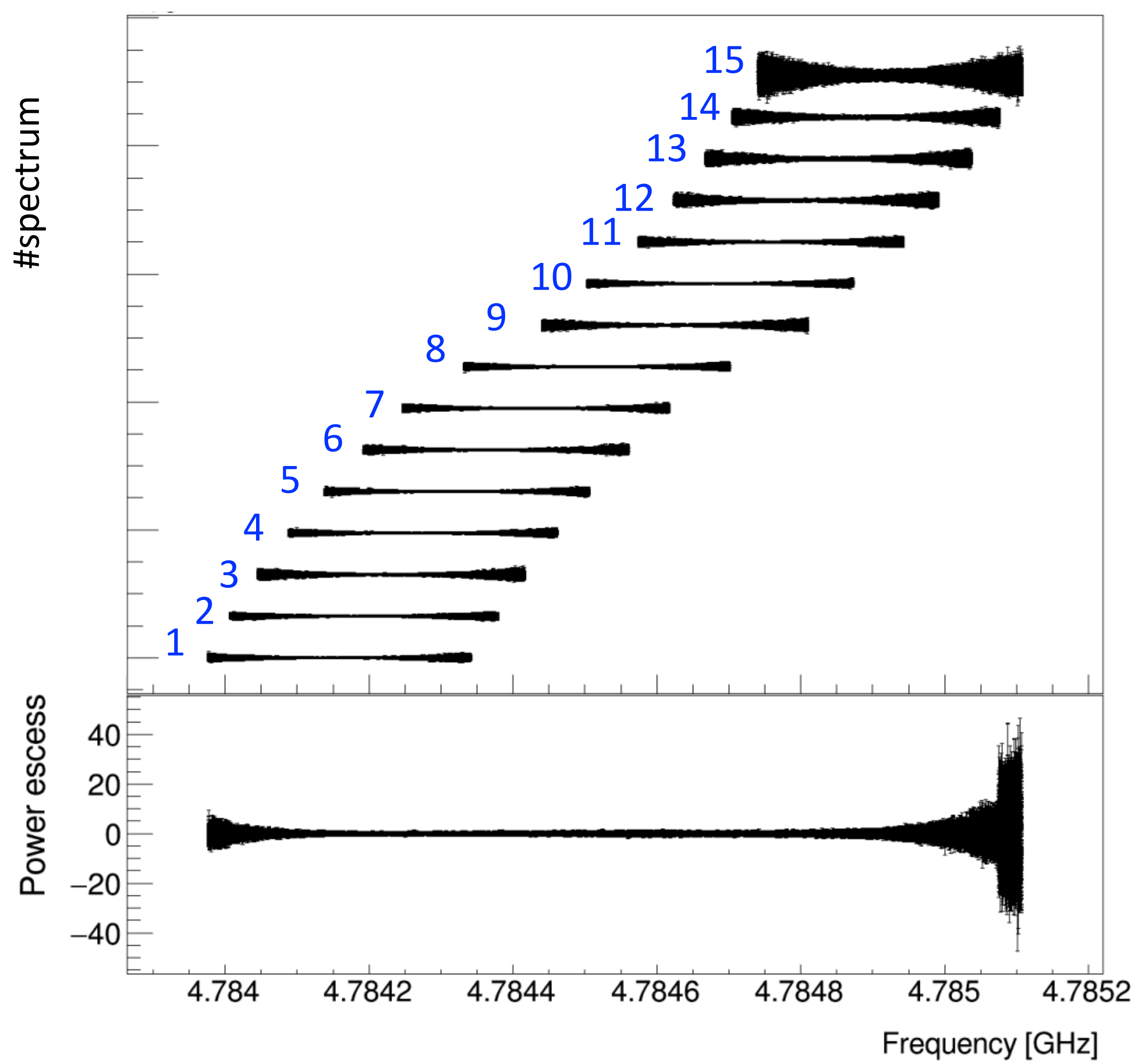
$$P_i^r(\nu) = \frac{k_B T_S(\nu)\Delta\nu_b P_i^n(\nu)}{P_i^a(\nu)}$$

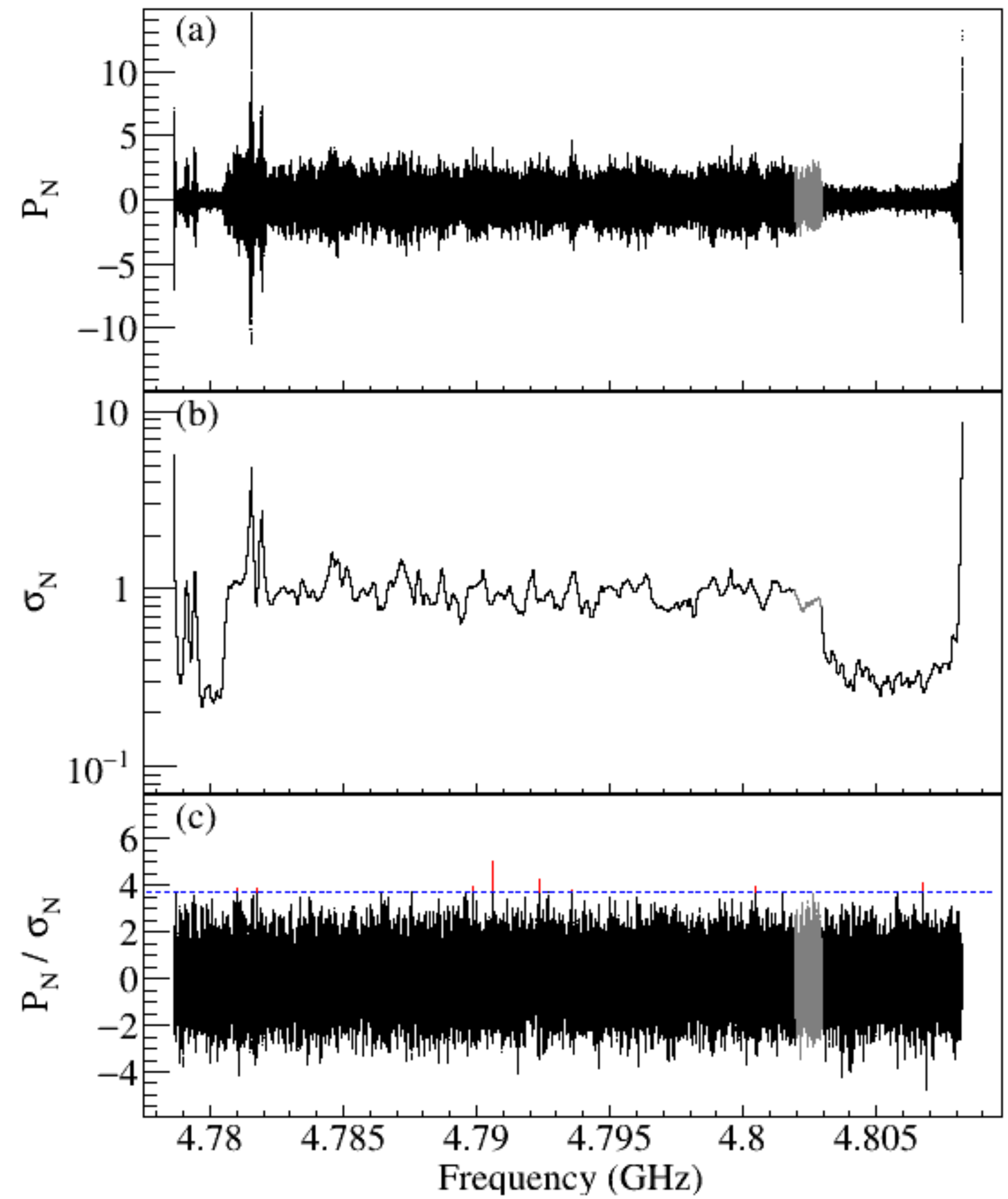
$$\sigma_i^r(\nu) = \frac{k_B T_S(\nu)\Delta\nu_b \sigma_i^n}{P_i^a(\nu)}$$

$$w_i(\nu) = \frac{(\sigma_i^r(\nu))^{-2}}{\sum_i(\sigma_i^r(\nu))^{-2}}$$

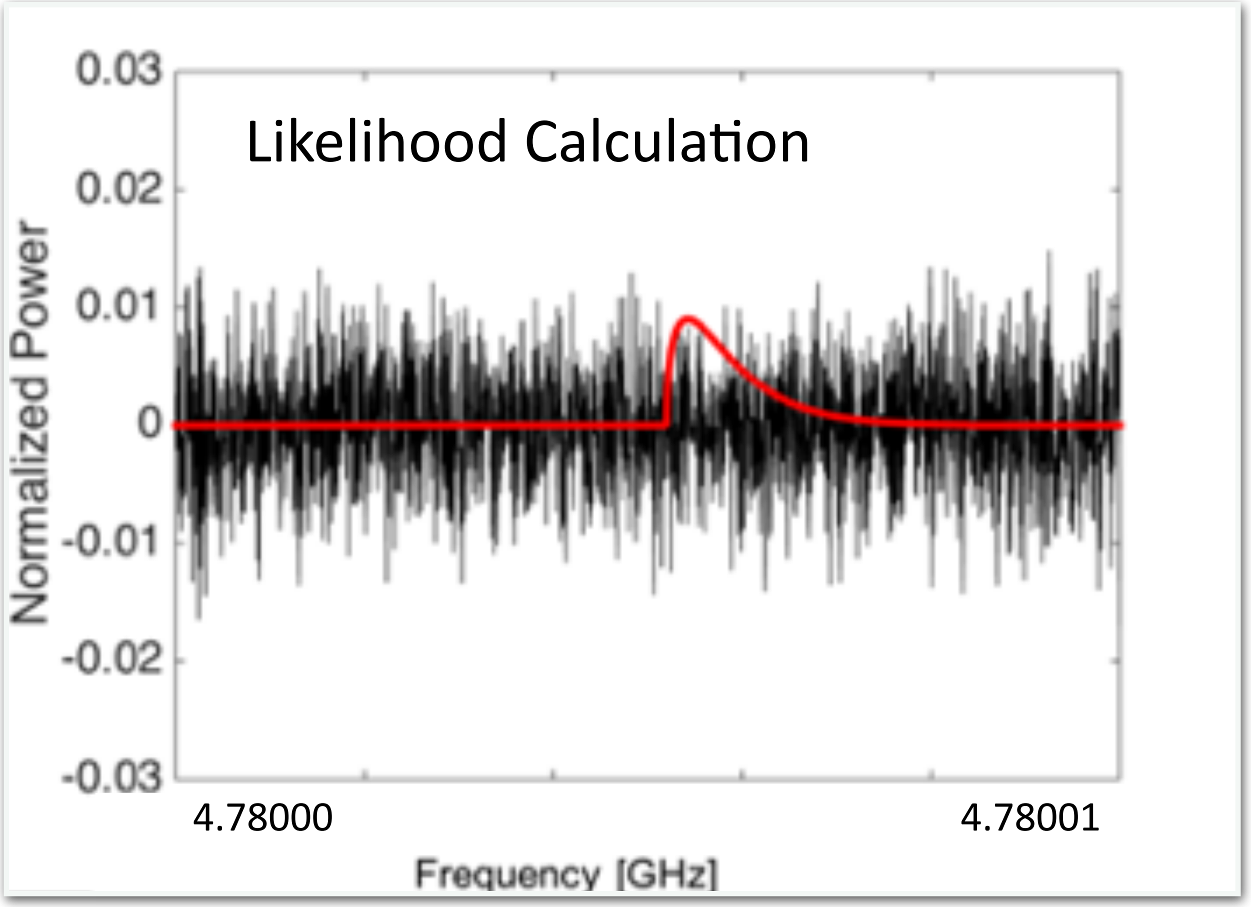
Grand Power Spectrum

$$P_{\mathrm{N}}(\nu) = \sum_i w_i(\nu) P_i^r(\nu) \qquad \sigma_{\mathrm{N}}(\nu) = \sqrt{\sum_i [w_i(\nu)\sigma_i^r(\nu)]^2}$$





Axion Signal Likelihood and Rescan Candidates



Expected DM Axion Signal:

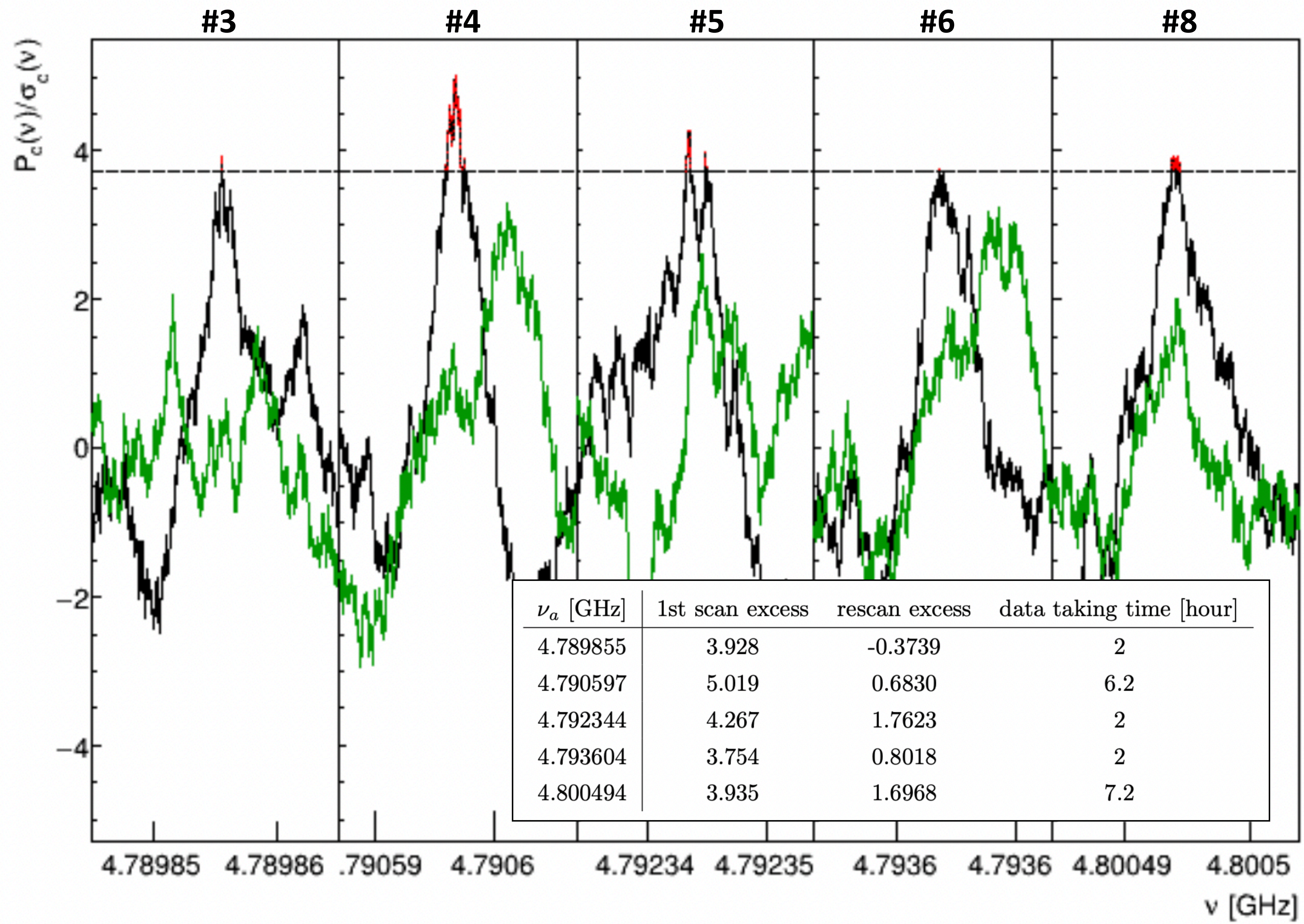
Maxwell-Boltzmann Distribution in frequency domain

$$\Phi_{\rm MB}(\nu) = \frac{2}{\sqrt{\pi}}\left(\sqrt{\frac{3}{2}}\frac{1}{r}\frac{1}{\nu_a\langle \mathbf{v}^2\rangle}\right)\sinh\left(3r\sqrt{\frac{2(\nu-\nu_a)}{\nu_a\langle \mathbf{v}^2\rangle}}\right) \times \exp\left(-\frac{3(\nu-\nu_a)}{\nu_a\langle \mathbf{v}^2\rangle}-\frac{3r^2}{2}\right),$$

No.	ν_a (GHz)	Excess (σ)	p_A	p_N	Rescan
1	4.780 998	3.881	0.0098	0.6443	✗
2	4.781 756	3.870	0.0043	0.7574	✗
3	4.789 855	3.928	0.0143	0.5808	○
4	4.790 597	5.019	0.0682	0.2557	○
5	4.792 344	4.267	0.1270	0.1519	○
6	4.793 604	3.754	0.1050	0.1820	○
7	4.800 494	3.935	0.0098	0.6442	✗
8	4.806 746	4.085	0.1569	0.1223	○

- **Rescan Criteria: $P_A > 0.01$**
  → 8 Rescan candidates
- **Rescan Operation: Aug. 2021**
  → No persistent signal is found
  setting upper bound in $g_{a\gamma\gamma}$

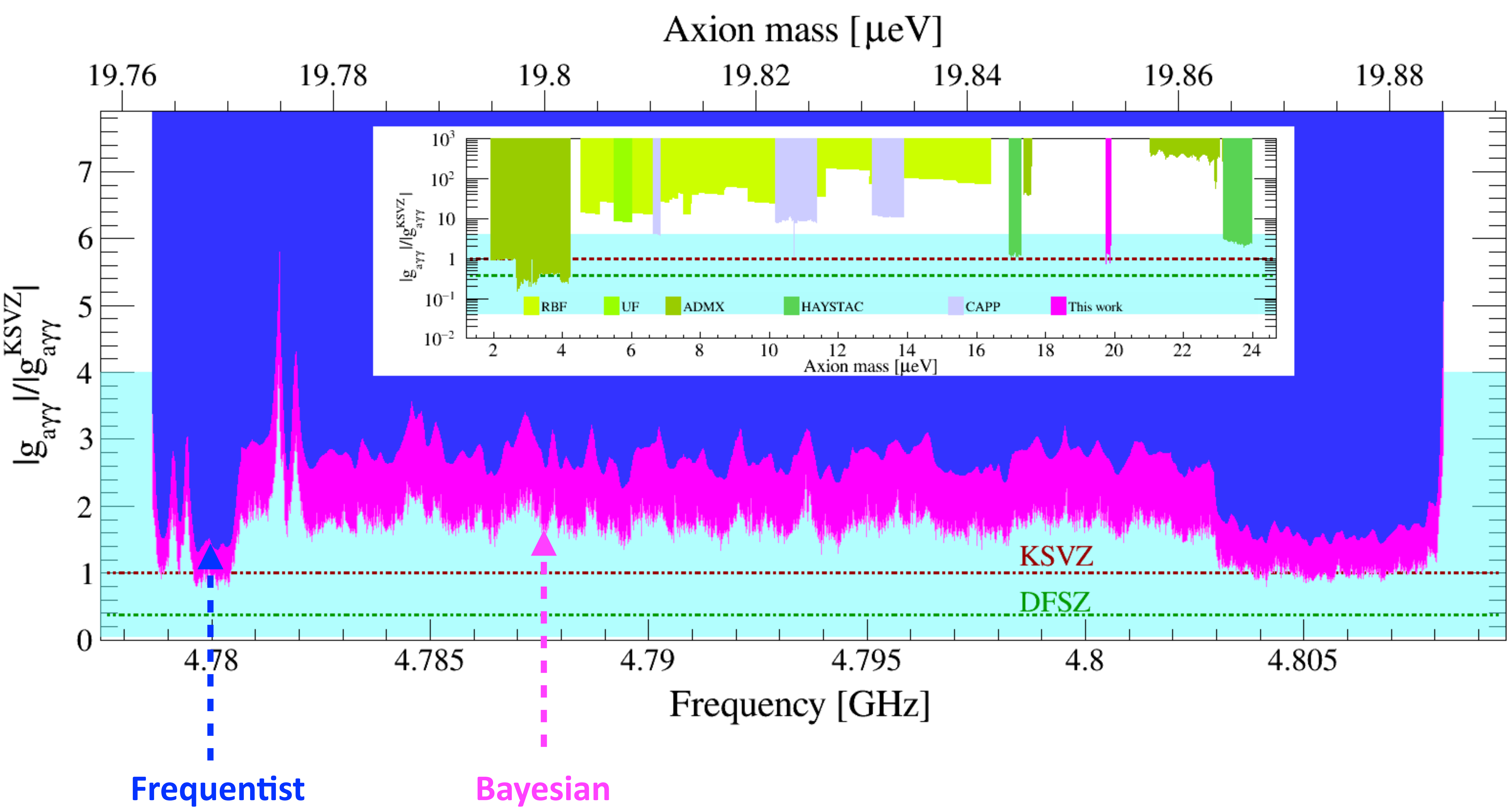
Rescan Results



ν_a [GHz]	1st scan excess	rescan excess	data taking time [hour]
4.789855	3.928	-0.3739	2
4.790597	5.019	0.6830	6.2
4.792344	4.267	1.7623	2
4.793604	3.754	0.8018	2
4.800494	3.935	1.6968	7.2

No significant enhancement of dark matter axion signal

Axion Dark Matter Search Results



Summary

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Searching for Invisible Axion Dark Matter with an 18 T Magnet Haloscope

Youngjae Lee,[1] Byeongsu Yang,[2] Hojin Yoon,[1] Moohyun Ahn,[3] Heejun Park,[2]
Byeonghun Min,[2] DongLak Kim,[2] and Jonghee Yoo[1,2,3]
[1]*Department of Physics, Korea Advanced Institute of Science and Technology, Daejeon 34141, Korea*
[2]*Center for Axion and Precision Physics Research, Institute for Basic Science, Daejeon 34051, Korea*
[3]*Department of Physics and Astronomy, Seoul National University, Seoul 08826, Korea*

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We report the first search results for axion dark matter using an 18 T high-temperature superconducting magnet haloscope. The scan frequency ranges from 4.7789 to 4.8094 GHz. No significant signal consistent with the Galactic halo dark matter axion is observed. The results set the best upper bound of axion-photon-photon coupling ($g_{a\gamma\gamma}$) in the mass ranges of 19.764 to 19.771 μeV (19.863 to 19.890 μeV) at $1.5 \times |g_{a\gamma\gamma}^{\mathrm{KSVZ}}|$ ($1.7 \times |g_{a\gamma\gamma}^{\mathrm{KSVZ}}|$), and 19.772 to 19.863 μeV at $2.7 \times |g_{a\gamma\gamma}^{\mathrm{KSVZ}}|$ with 90% confidence level, respectively. This remarkable sensitivity in the high mass region of dark matter axion is achieved by using the strongest magnetic field among the existing haloscope experiments and realizing a low-noise amplification of microwave signals using a Josephson parametric converter.

More details: PRD 106 092007 (2022)