CAPP-8TB: Axion Dark Matter Search around 6.7 μeV

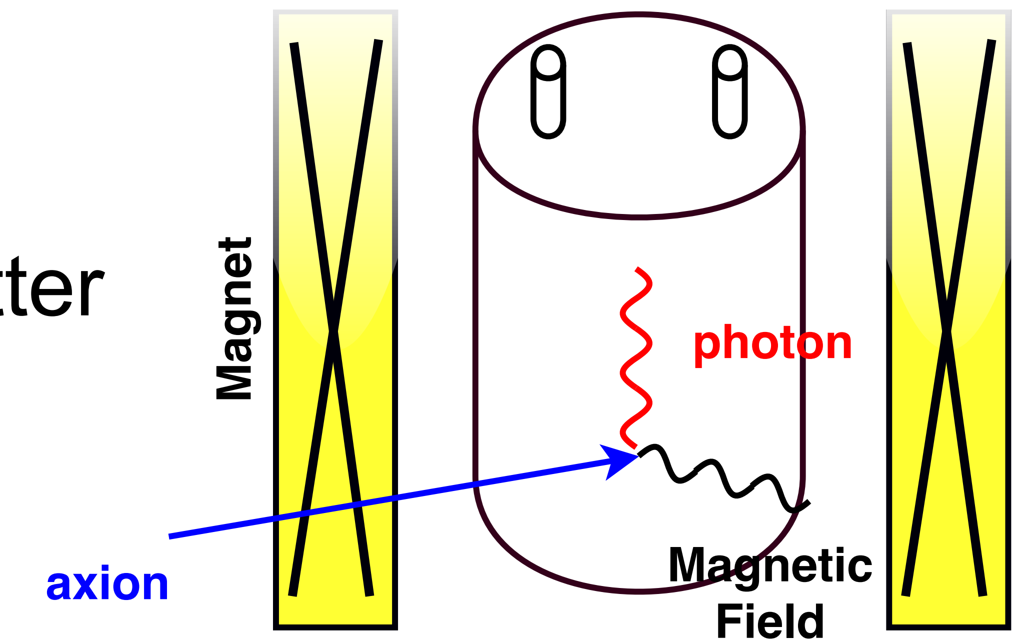
Soohyung Lee
on behalf of the CAPP-8TB team
Center for Axion and Precision Physics Research
Institute for Basic Science
June 9, 2020
The 4th TAU collaboration meeting

- Strong CP problem
  - CP violation is mathematically possible in QCD, however, it has never been found in experiments
  - R. Peccei and H. Quinn *[1]* proposed the PQ mechanism to solve the strong CP problem
  - F. Wilczek *[2]* and S. Weinberg *[3]* showed that PQ mechanism results in a new particle, axion (PQWW axion), however, it was quickly excluded by experiments

- "Invisible" axion
  - Kim-Shifman-Vainshtein-Zakharov (KSVZ) *[4,5]* model introduces a heavy quark doublet
  - Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) *[6,7]* model couples with SM (contains two Higgs doublets)

[1] R. Peccei and H. R. Quinn, Phys. Rev. Lett. ***38****, 1440 (1977)*
[2] F. Wilczek, Phys. Rev. Lett. ***40****, 279 (1978)*
[3] S. Weinberg, Phys. Rev. Lett. ***40****, 223 (1978)*
[4] J. E. Kim, Phys. Rev. Lett. 32, 103 (1979)
[5] M. A. Shifman, A. I. Vainshtein, and V. I. Zakharov, Nucl. Phys. B ***166****, 493 (1980)*
[6] M. Dine, W. Fischler, and M. Srednicki, Phys. Lett. B ***104****, 199 (1981)*
[7] A. Zhitnitsky, Sov. J. Nucl. Phys. ***31****, 260 (1980)*

- Axion is thought to be extremely light and stable, it became a good candidate of the dark matter



Tunable Resonant Cavity

- P. Sikivie *[8]* proposed an experimental technique to search the axion dark matter
  - Axion converts into a photon under an external magnetic field through inverse Primakoff effect
  - Microwave resonant cavity picks up its signal to bring axion to visible world
  - From the Lagrangian for the coupled axion and photon fields:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

a: axion field
m_a: axion mass
$g_{a\gamma\gamma}$: axion-photon coupling

Modified Maxwell equations:

$$\nabla \cdot \mathbf{E} = g_{a\gamma\gamma}\mathbf{B} \cdot \nabla a$$

$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = g_{a\gamma\gamma}(\mathbf{E} \times \nabla a - \mathbf{B}\partial_t a)$$

$$\nabla \times \mathbf{E} + \partial_t \mathbf{B} = 0$$

$$\nabla \cdot \mathbf{B} = 0$$

*[8] P. Sikivie, Phys. Rev. Lett. **51**, 1415 (1983)*

Axion Conversion Power

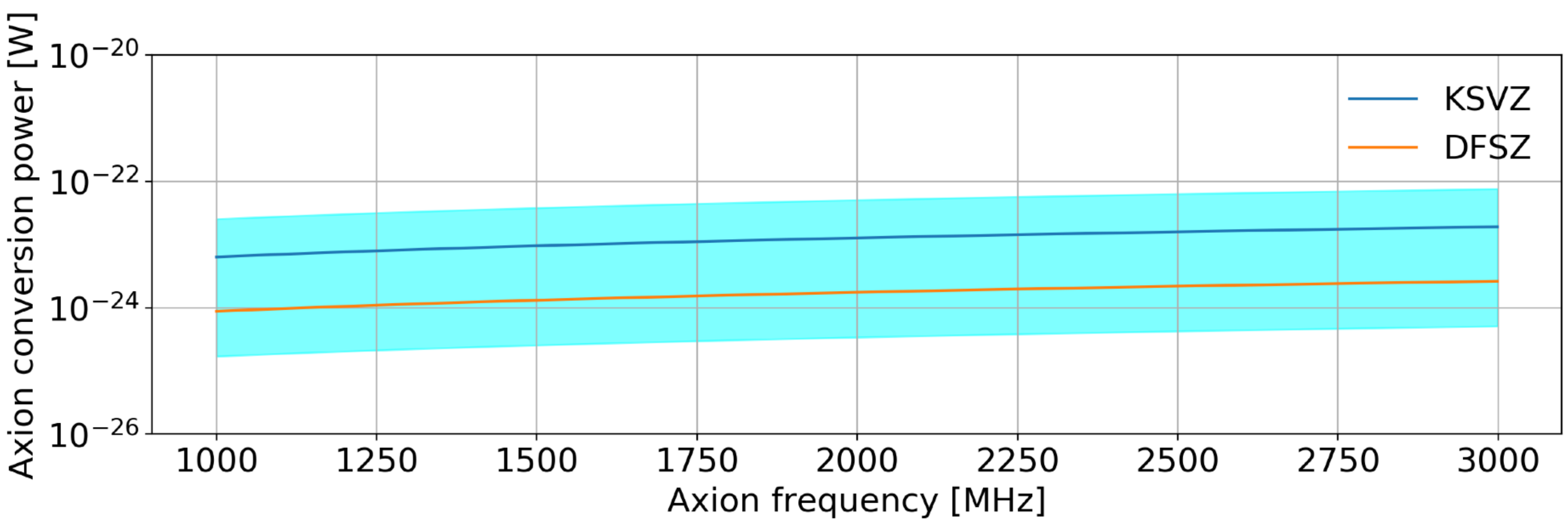
- Axion conversion power in a resonant cavity

$$P_s = g_{a\gamma\gamma}^2 \left(\frac{\rho_a \hbar^2}{m_a^2 c}\right) \left(\omega \frac{1}{\mu_0} B^2 V\right) C_{nlm} Q_L \frac{\beta}{1+\beta}$$

$g_{a\gamma\gamma}$: axion-photon coupling strength
ρ_a: local dark matter density (0.45 GeV/cm^3)
m_a: axion mass
ω: resonant frequency of the cavity matched with the axion mass

B: external magnetic field
V: cavity volume
β: antenna coupling coefficient
C_{nlm}: cavity form factor of TM_{nlm} mode
Q_L: loaded quality factor of cavity

- With B = 8 T, V = 3.5 liters, C_{010} = 0.6, Q_L = 30,000, β = 2,



Axion Scan Rate

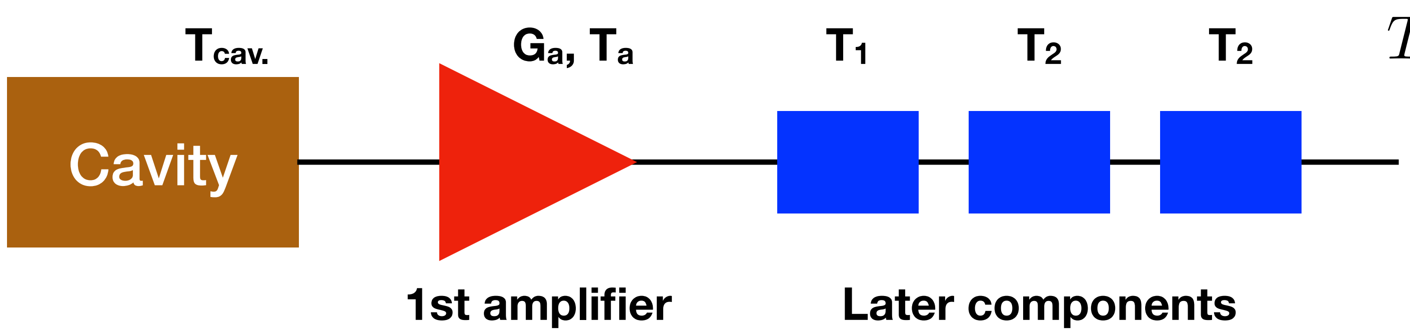
- Scan rate tells us how fast an experiment is capable to scan a given frequency range

$$\frac{df}{dt} \propto \eta \frac{B^4 V^2 C_{nlm}^2 Q_L}{T_{\mathrm{sys.}}^2}$$

η: data acquisition efficiency
$T_{sys.}$: system noise temperature

- Stronger magnet (B↑), bigger cavity (V↑), better materials (C_{nlm}↑, Q_L↑), and lower noise temperature ($T_{sys.}$↓) increases a performance of an experiment

- $T_{sys.}$ consists of a thermal noise temperature of a cavity and noise temperatures of a signal receiver chain
  - With an amplifier of a good gain, noise temperatures from later components are negligible

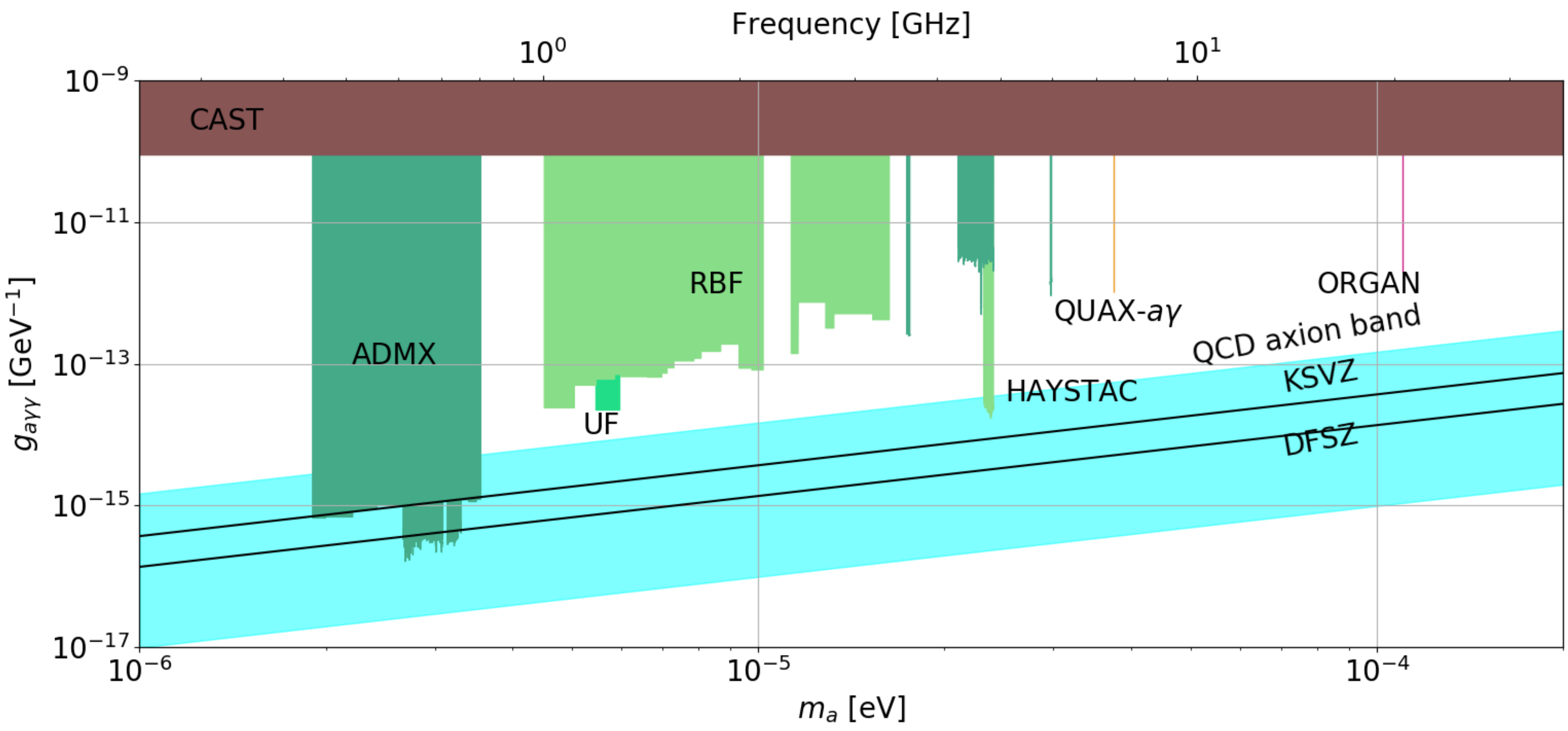


$$T_{\mathrm{sys.}} = T_{\mathrm{cav.}} + T_a + \frac{1}{G_a}(T_1 + T_2 + T_3 + \cdots)$$

Typical gain of a low-noise amplifier >30 dB (>1000)

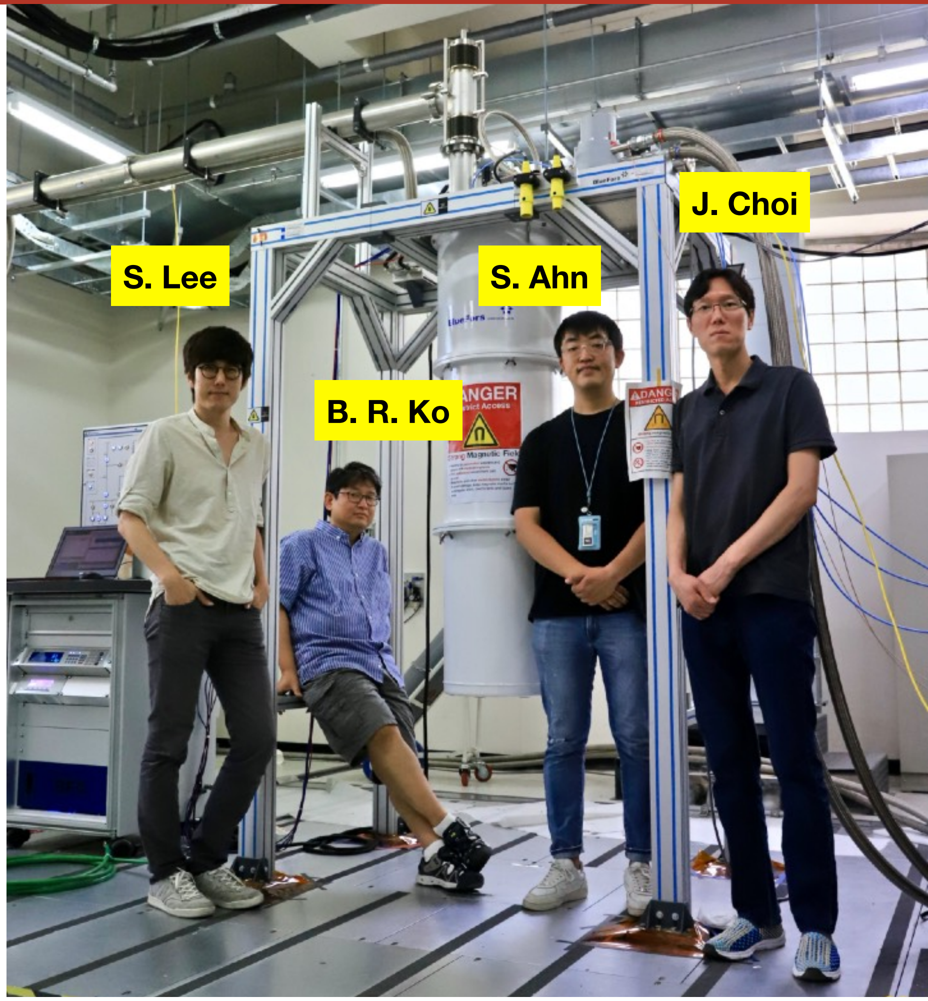
Axion Mass Exclusions (90 days ago)

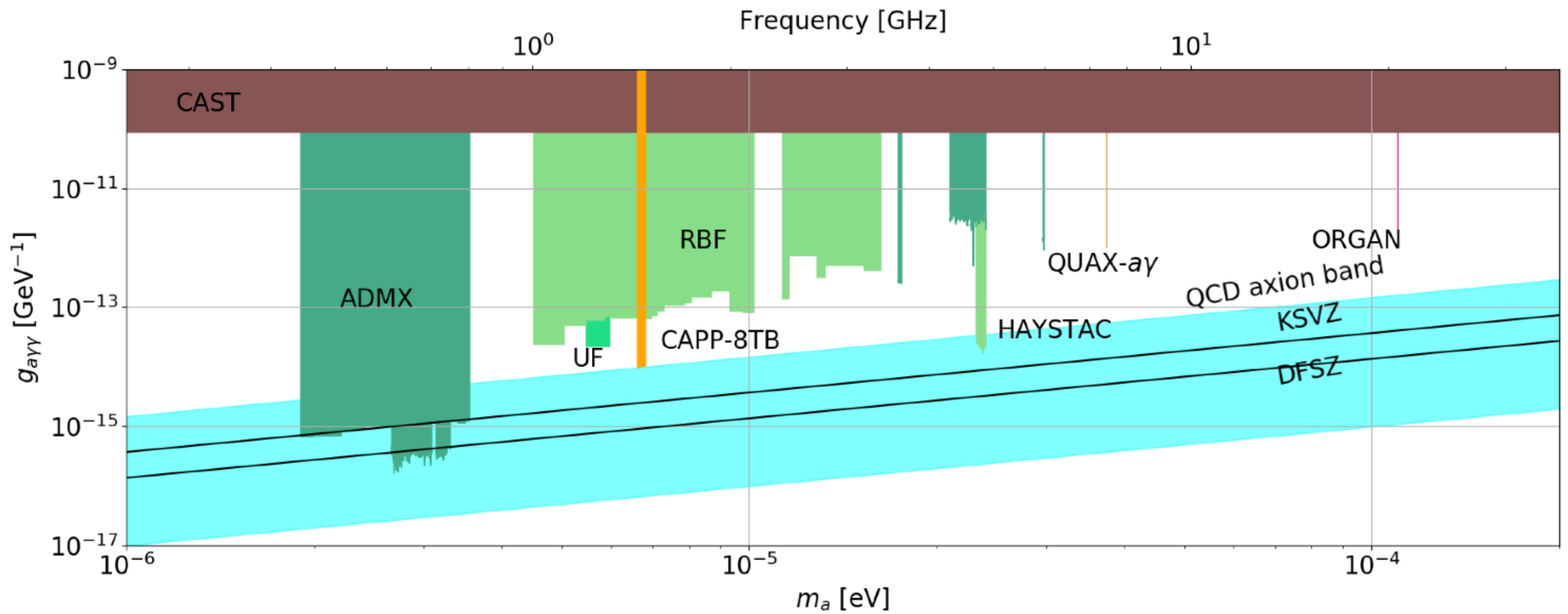
- Various experiments searched over various masses with sensitivities
  - Vast mass regions need to be explored



The CAPP-8TB Experiment

- **CAPP-8TB**
  - Axion haloscope with 8 T, Big bore superconducting magnet
  - *S. Ahn (KAIST), J. Choi (IBS/CAPP, now at KASI), B. R. Ko (IBS/CAPP), S. Lee (IBS/CAPP),* and *Y. K. Semertzidis (IBS/CAPP, KAIST)*
  - Established in 2017
  - Capable to scan 1.43 - 1.7 GHz (5.91 - 7.03 μeV)
  - **Phase 1: 1.60 - 1.65 GHz (6.62 - 6.82 μeV)**
  - Targeting to touch QCD axion band



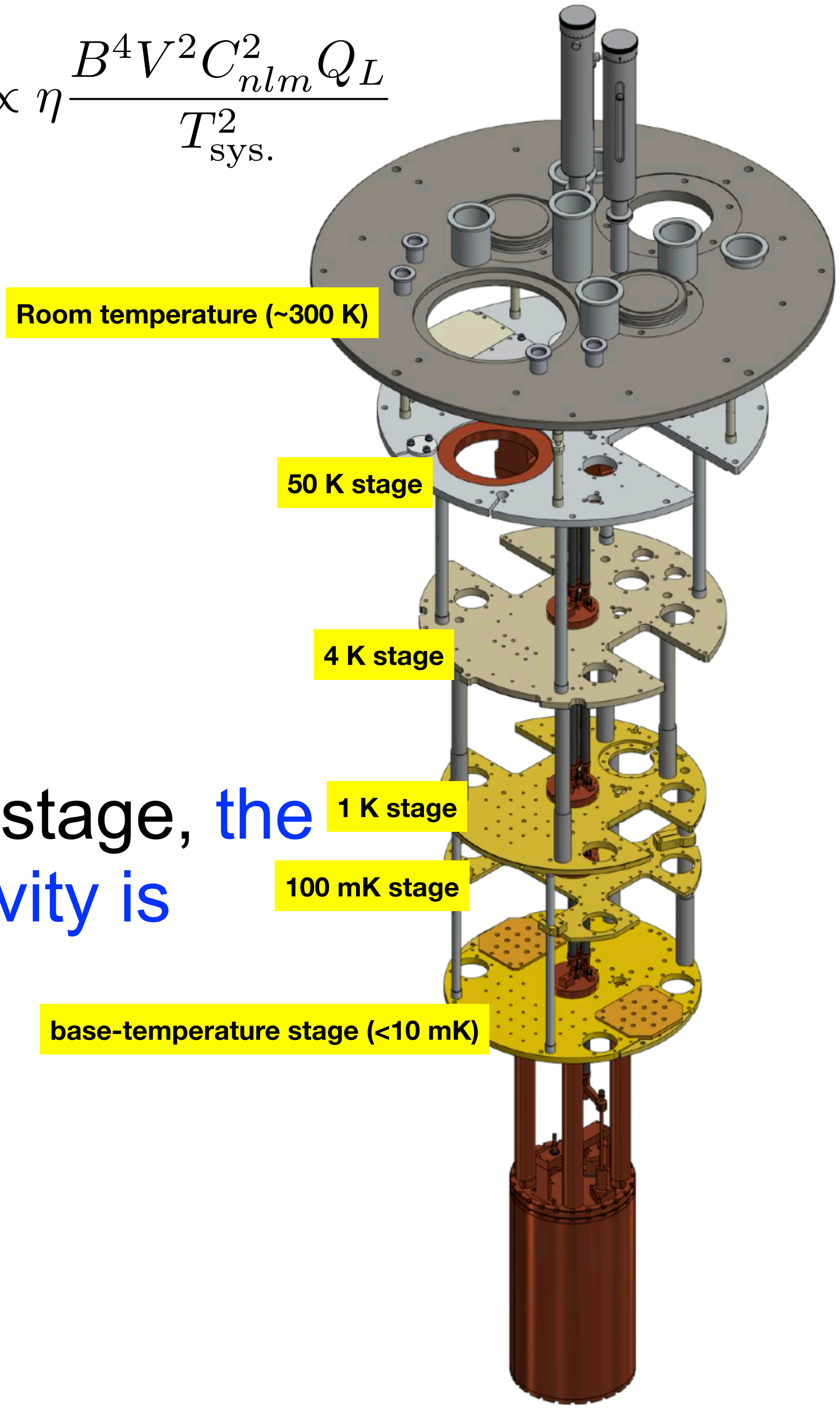


Dilution Refrigerator

- To maintain the physical temperature of the microwave resonant cavity as low as possible, BlueFors dilution refrigerator LD-400 is employed
  - Base temperature: < 10 mK
  - Cooling power: 16 μW at 20 mK
  - Closed system of ^{3}He and ^{4}He mixture

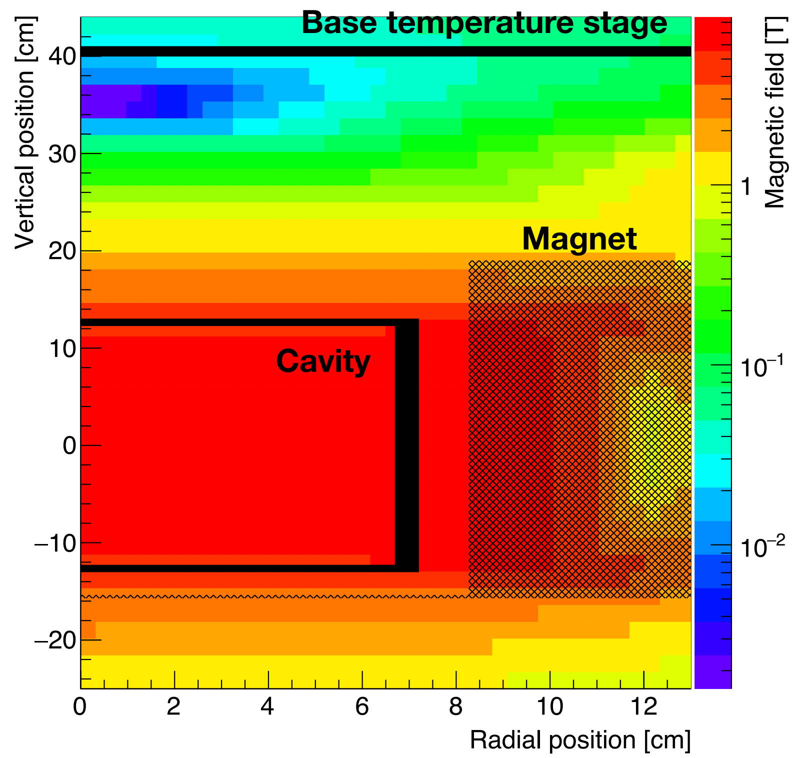
$$\frac{df}{dt} \propto \eta \frac{B^4 V^2 C_{nlm}^2 Q_L}{T_{\mathrm{sys.}}^2}$$

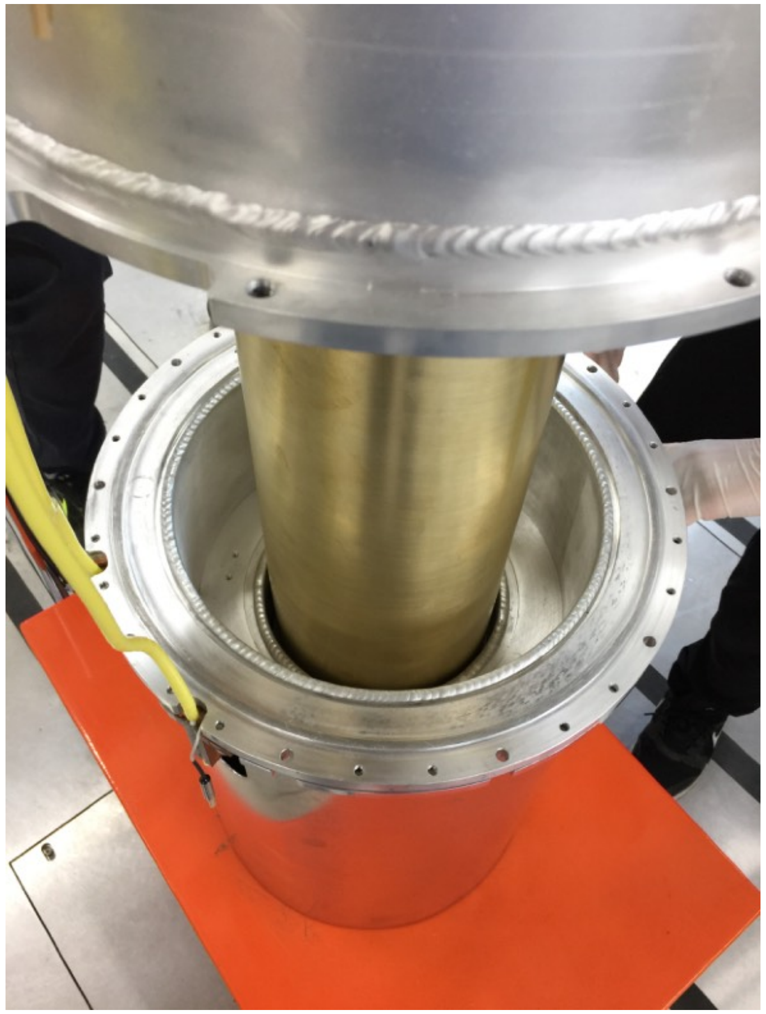
- Using a heater at the base temperature stage, the physical temperature of the resonant cavity is maintained at 50 mK

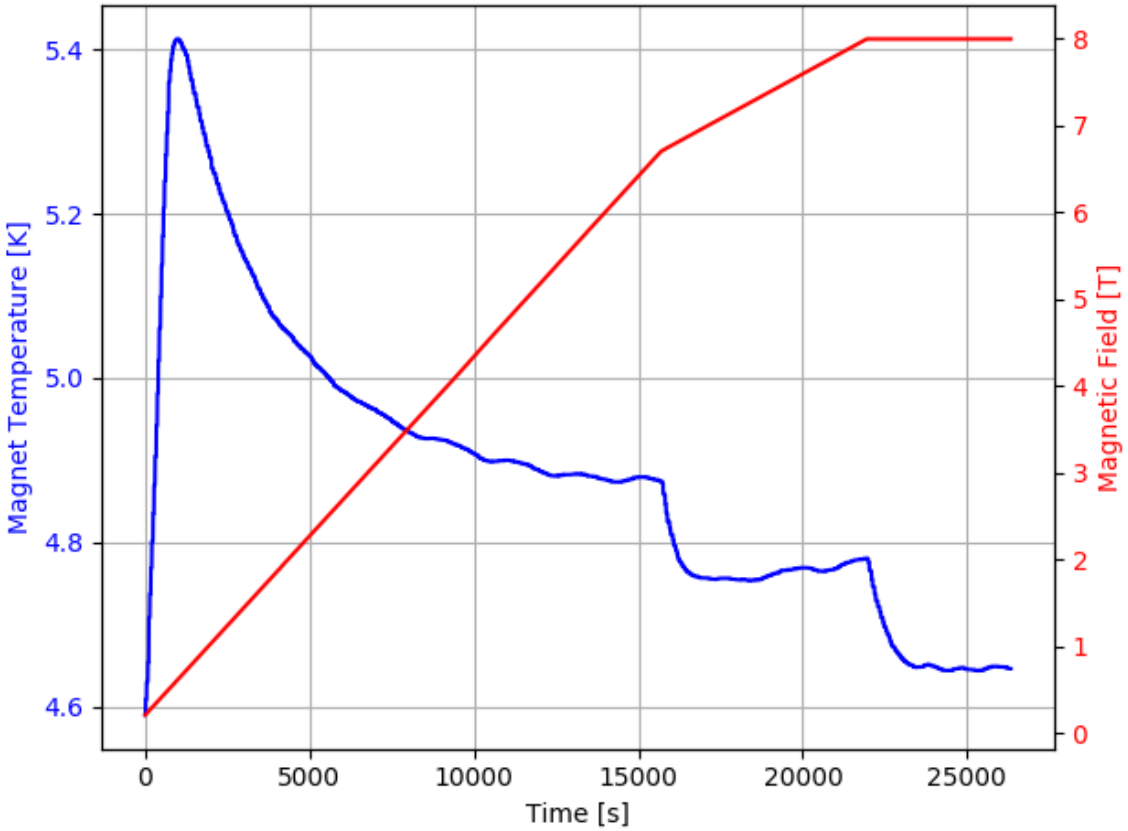


Superconducting Magnet

- American Magnetics Inc. superconducting solenoid magnet is used to provide an external magnetic field
  - Nominal B field: 8 T @ 96.56 A
  - Current is maintained within ±0.15 mA
  - Clear inner bore: 165 mm
  - Average B field in the resonant cavity: **7.3 T**



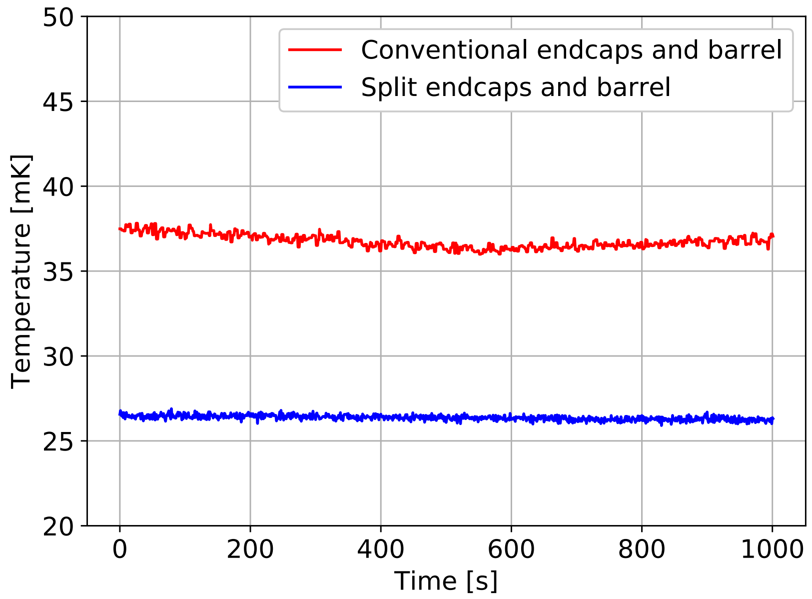


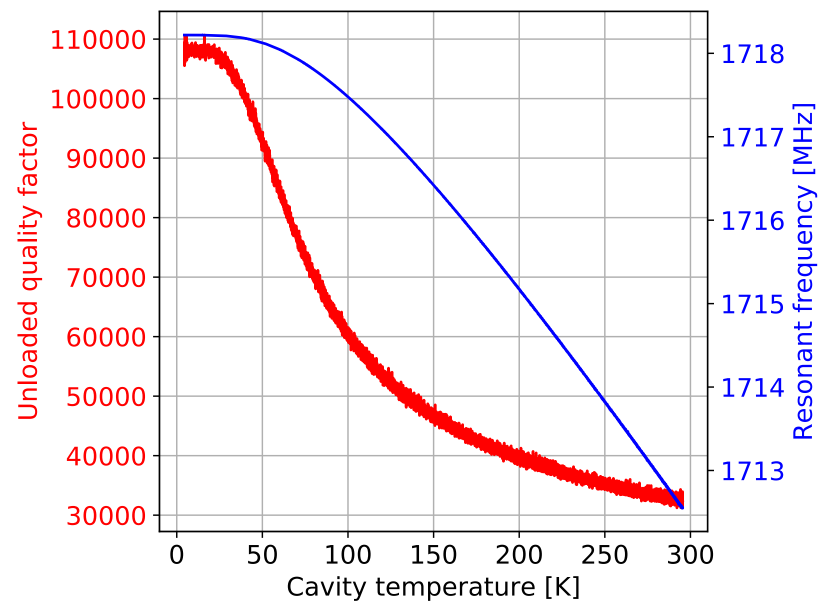


Microwave Resonant Cavity

- Microwave resonant cavity is made of oxygen-free high conductivity copper (OFHC)
  - Inner diameter: 134 mm
  - Inner length: 246 mm
  - Inner volume: 3.5 liters
  - Resonant frequency: ~1718 MHz (Q_0 ~ 110k)

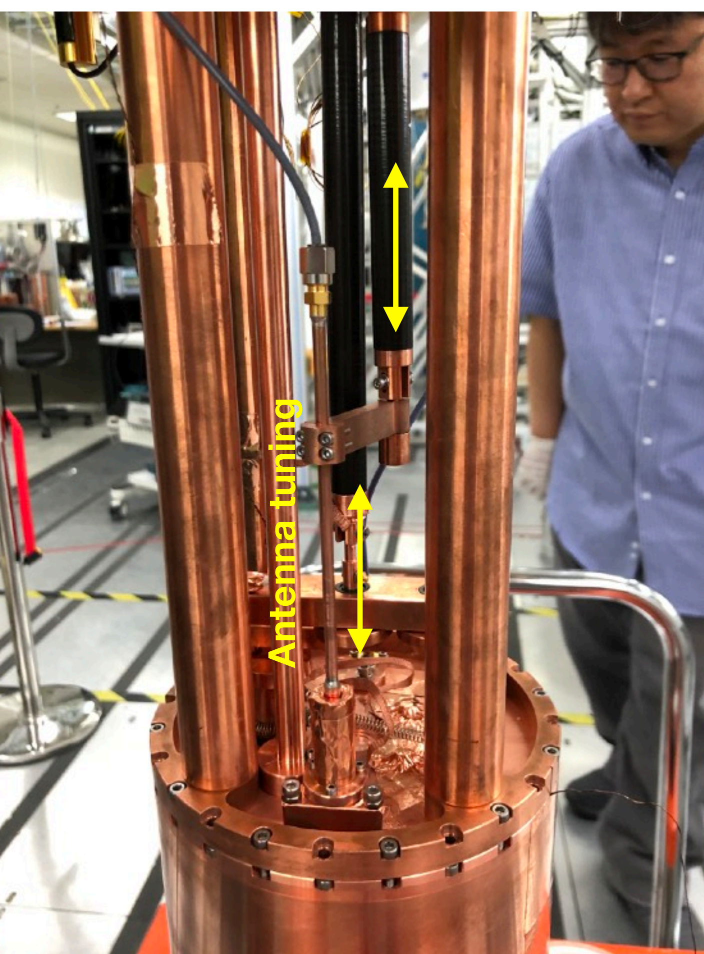
- The cavity is vertically split into two pieces:
  - To maintain lower temperature
  - To be safe in case of magnet quench

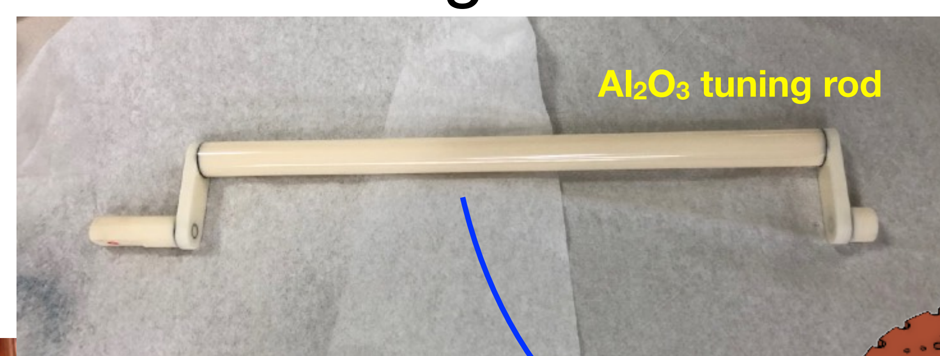


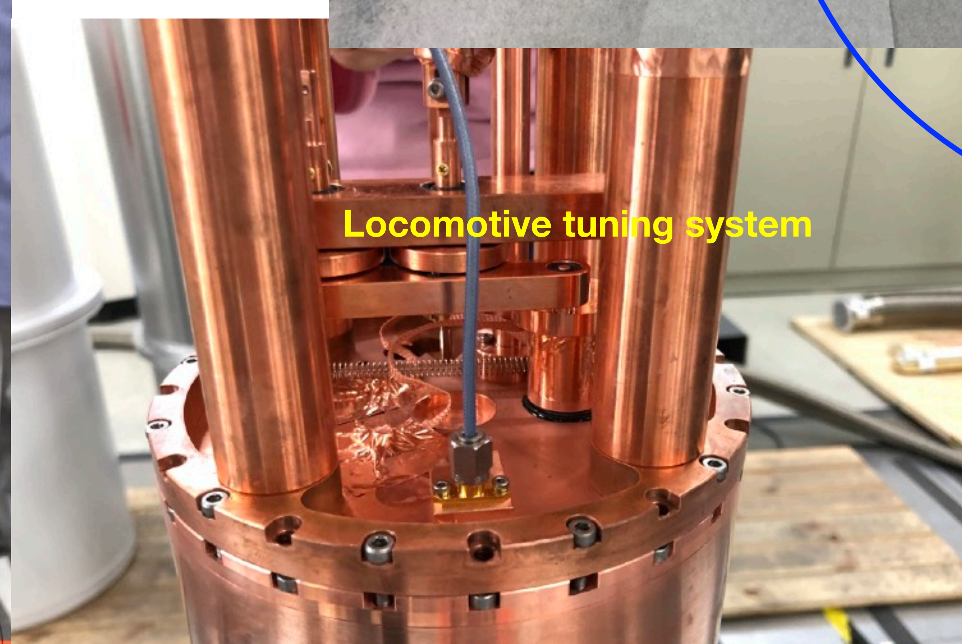


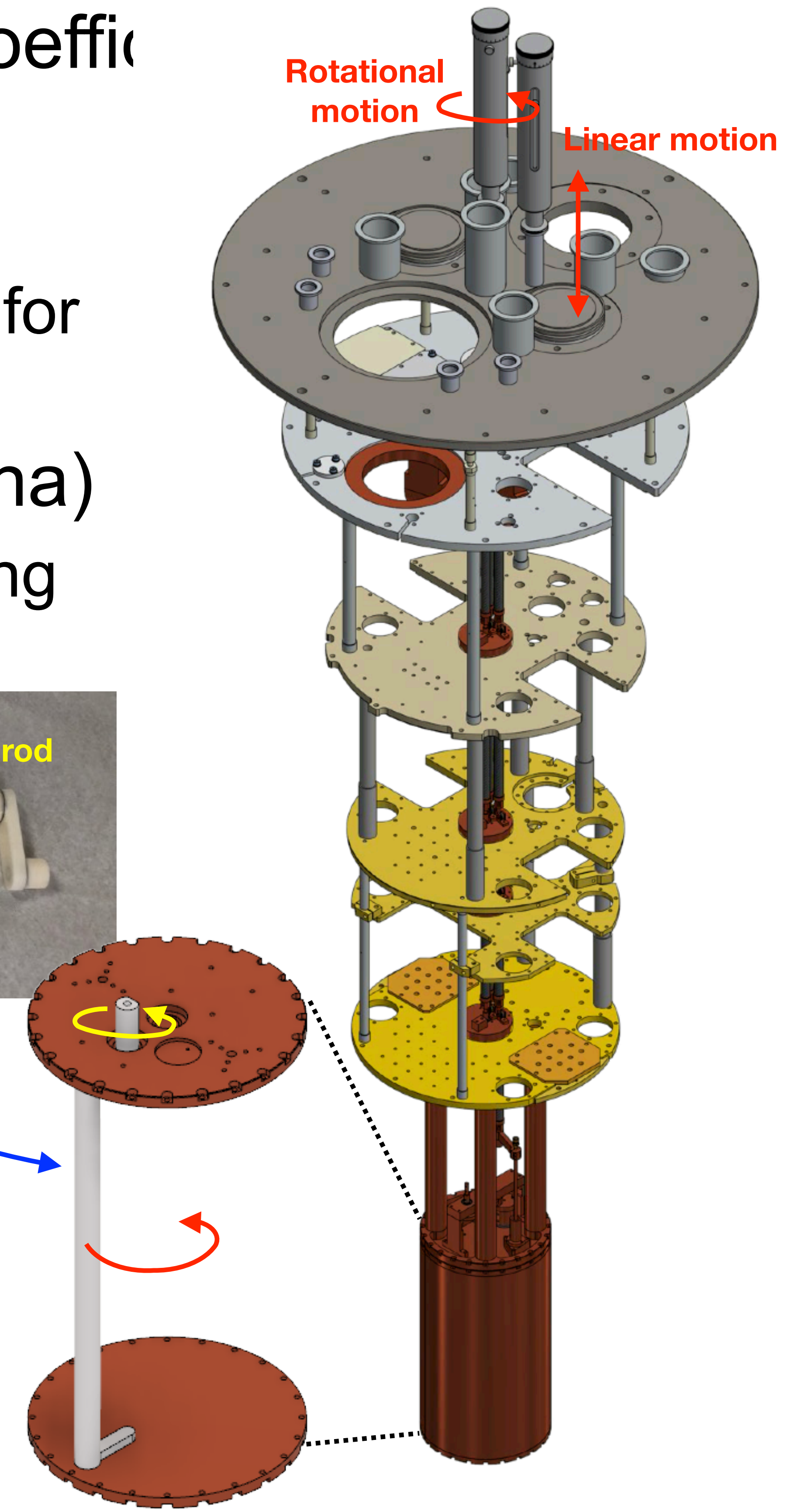
Tuning Mechanism

- Resonant frequency and antenna coupling coeffi are tuned in a tuning mechanism
  - Stepping motors drive the tuning mechanism
  - Carbon fiber reinforced polymer (CFRP) is used for driving shafts to block heat penetrations
- Resonant frequency tuning with Al_2O_3 (alumina)
  - Locomotive frequency tuning translates the driving axle to the rotational axle of the tuning rod



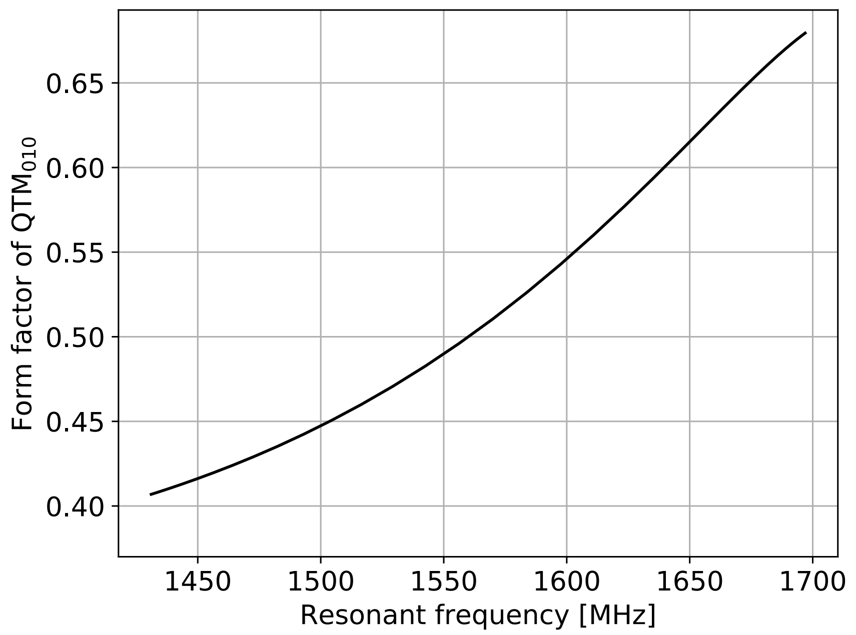


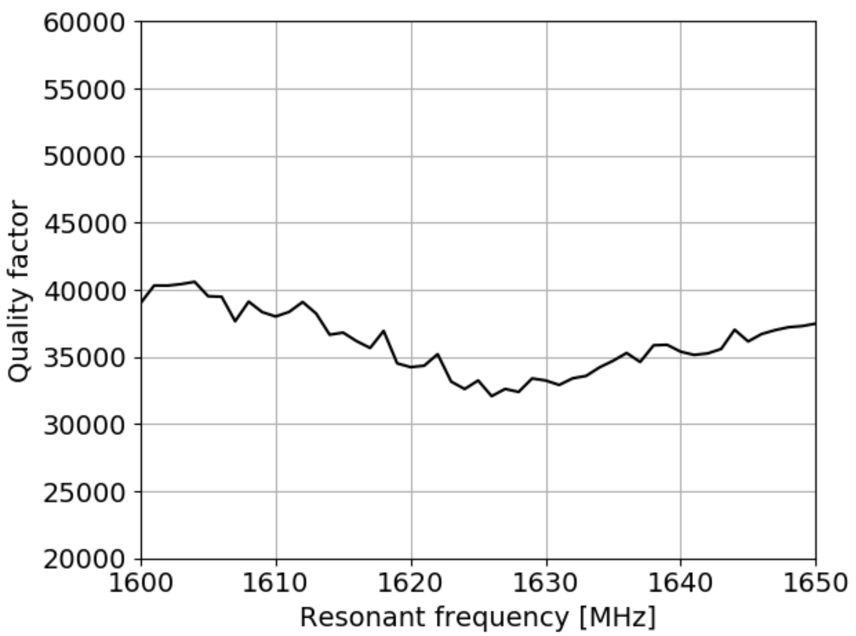


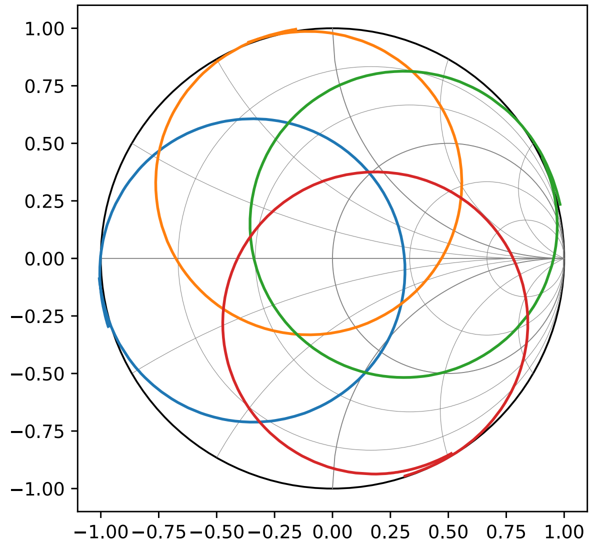


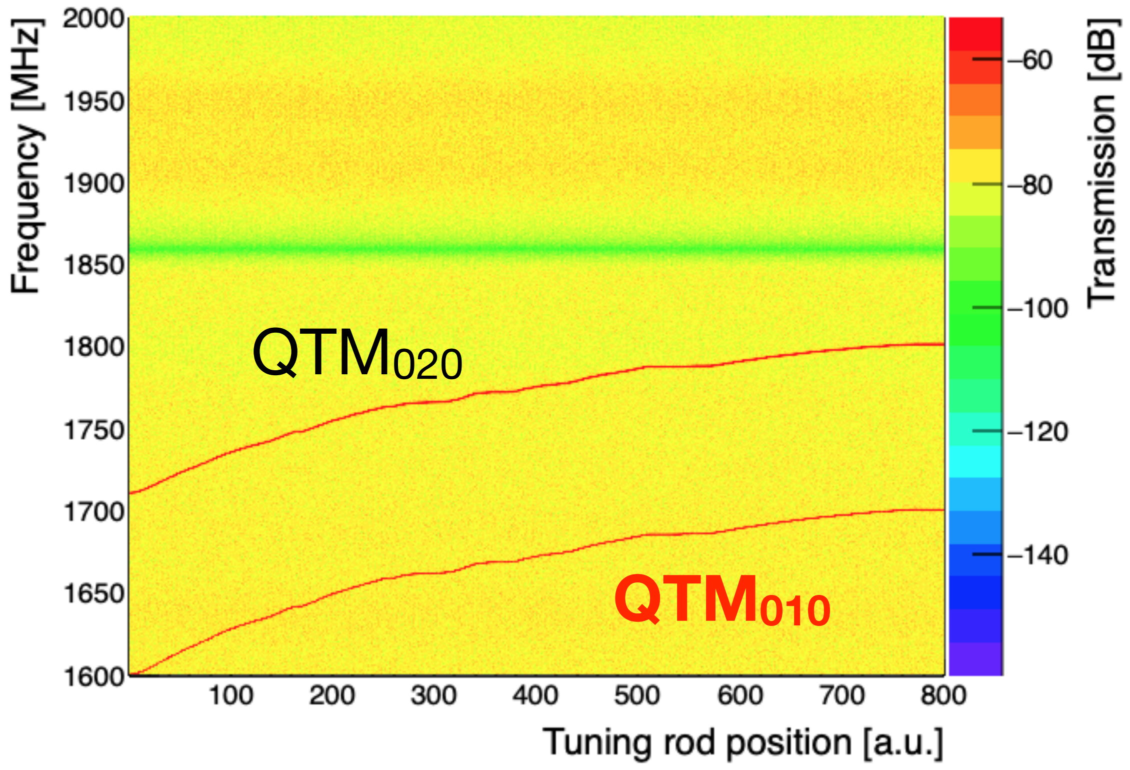
Tuning Mechanism

- With Al_2O_3 tuning rod, resonant frequency can be tuned from 1.43 GHz to 1.7 GHz
  - For phase 1, frequency range of 1.6 - 1.65 GHz is chosen
  - $Q_L > 30{,}000$ with $\beta \sim 1.75$
- Simulation and measurement show that there is no mode-crossing (or mode-mixing)
  - No loss of sensitivity in the frequency region
- Tuning is typically done in a minute

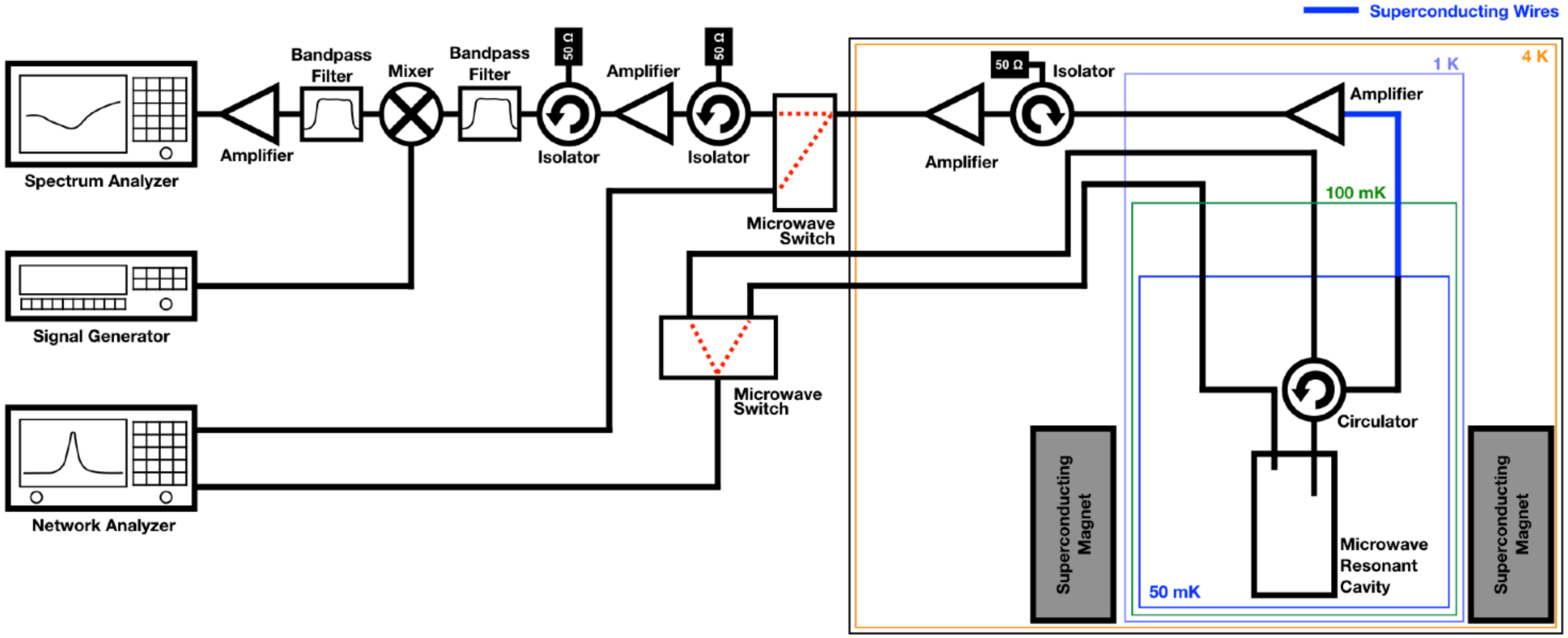


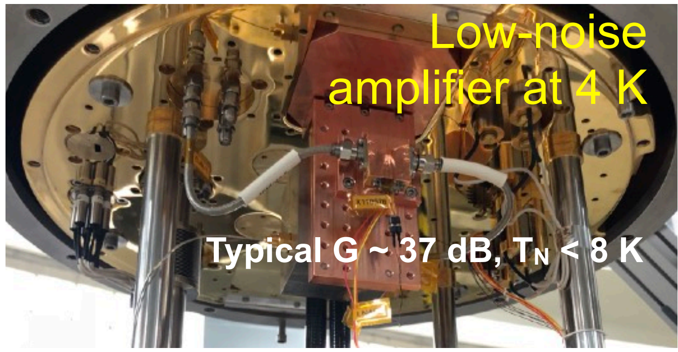


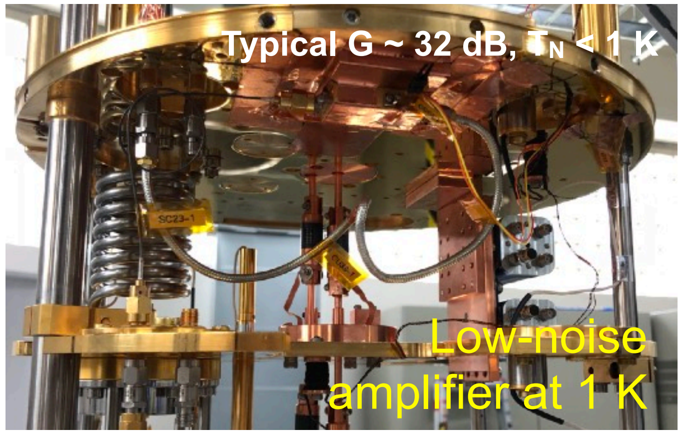




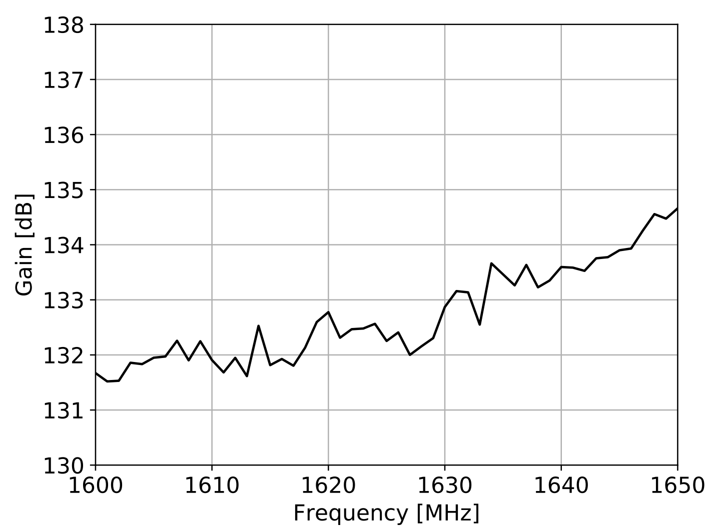
Microwave Receiver Chain

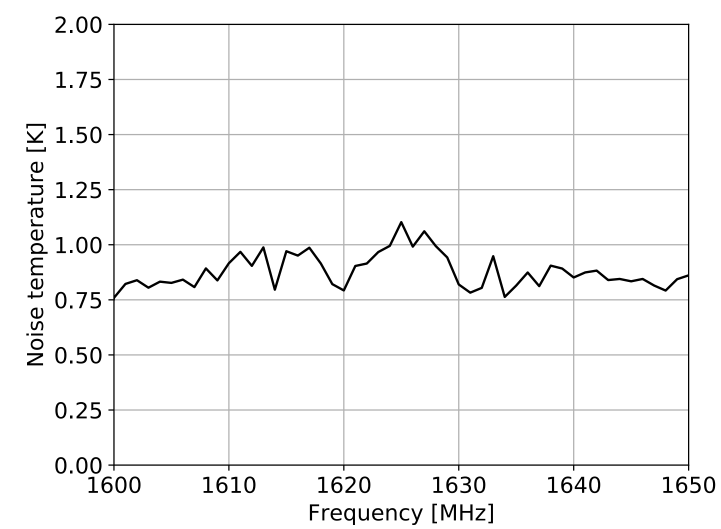






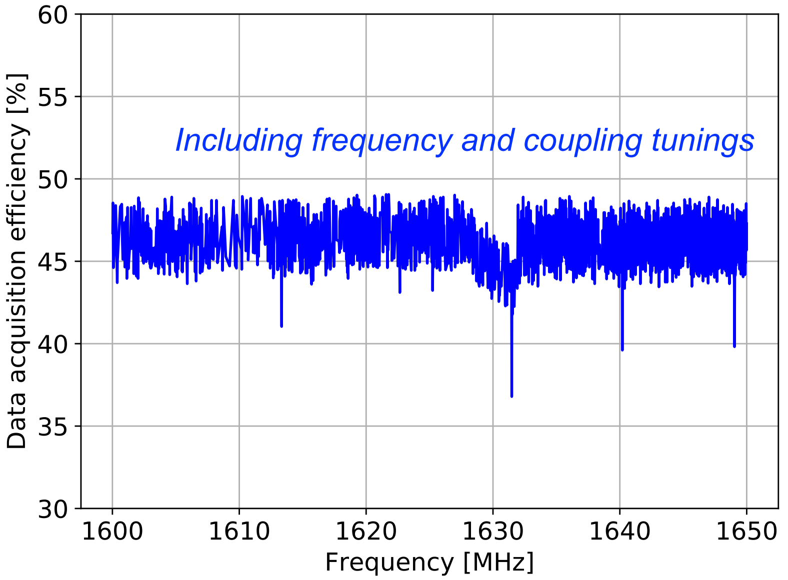
- Pickup signal is processed through a microwave receiver chain
  - Two cryogenic low-noise amplifiers at 1 K and 4 K stages
  - Total gain: ~133 dB
  - System noise temperature: **~0.9 K**
  - Cavity property and pickup power are measured by a network analyzer and a spectrum analyzer, respectively

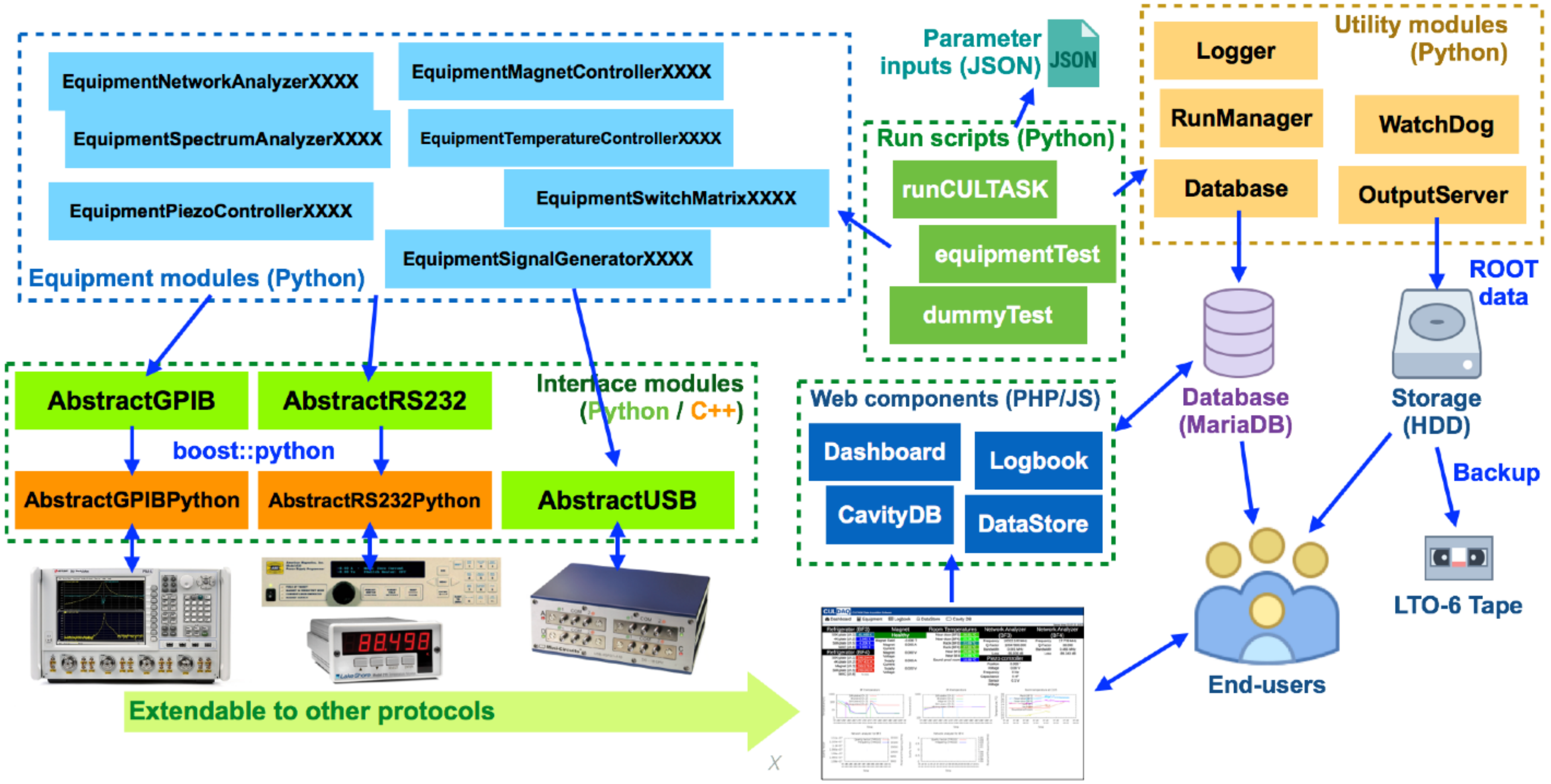




Data Acquisition

- Home-grown DAQ software (CULDAQ) controls and monitors the experiment
  - Various interfaces are supported (GPIB, USB, RS-232, Ethernet, …)
  - Data is written in ROOT format
  - Overall DAQ efficiency: ~40% (including tuning)





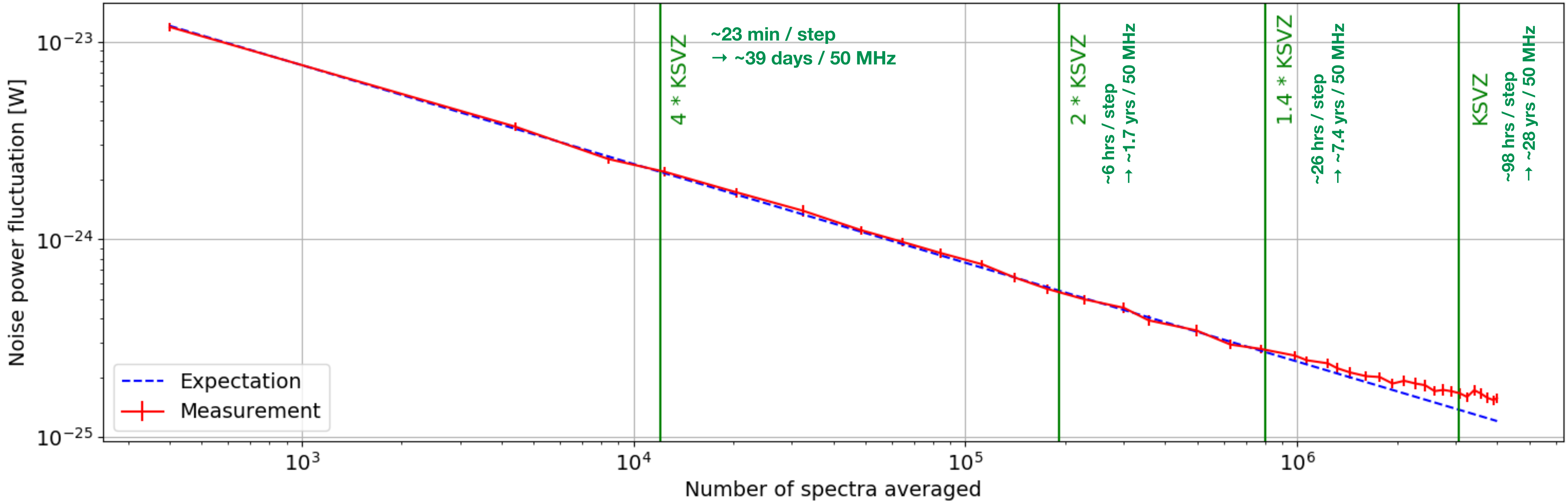
S. Lee, J. Phys.: Conf. Ser. ***898*** *(2017) 032035*

Detector Resolution

- The system may not be capable to reach a certain level of sensitivity due to vibrations, performance fluctuations, …
  - Fluctuation in noise power is the measure of detector resolution

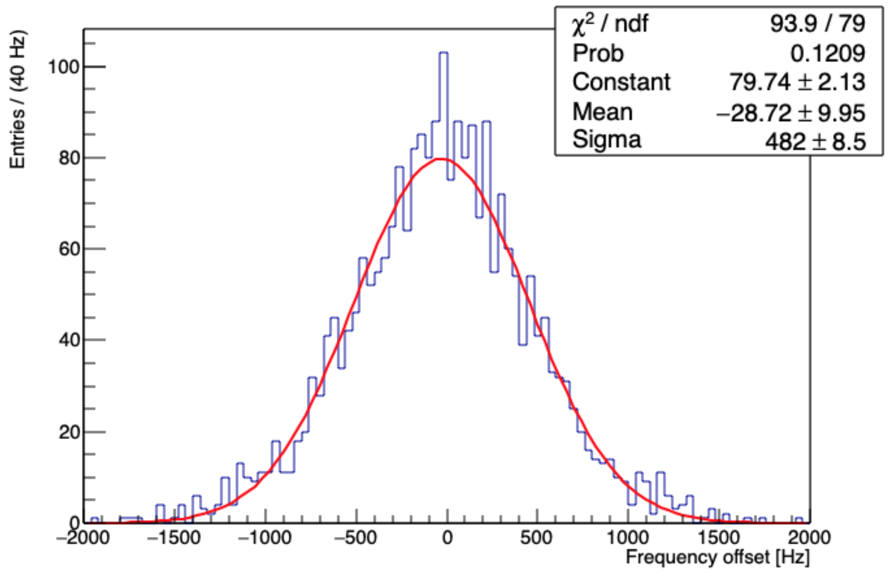
$$SNR = \frac{P_s}{\delta P_N} = \sqrt{N}\frac{P_s}{P_N}$$

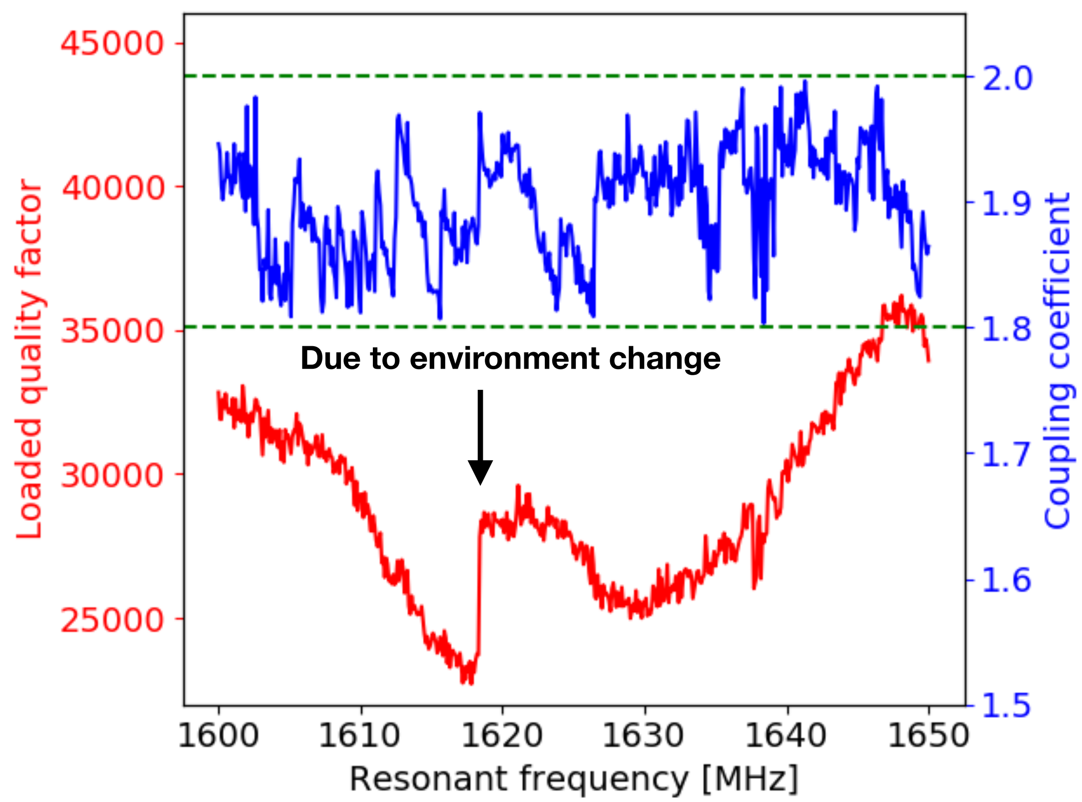
- CAPP-8TB is capable to reach ~1.4 × KSVZ
  - QCD axion band (= 4 × KSVZ) → ~39 days for 50 MHz scan
  - 1.4 × KSVZ → ~7.4 years for 50 MHz scan

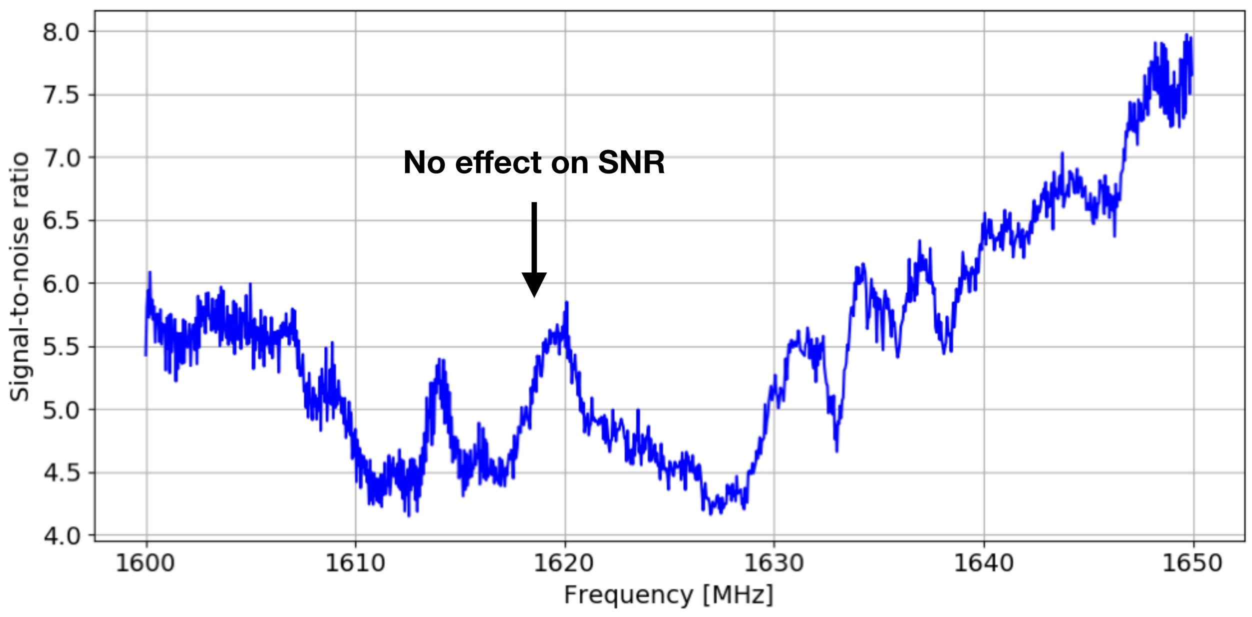


Physics Run

- Phase 1 data was taken from Sep 25 — Nov 11 in 2019 including rescan for problematic frequency steps due to spurious peaks
  - Frequency range: 1.6 - 1.65 GHz
  - Frequency step of 20 kHz with a resolution bandwidth of 20 Hz
  - 12,000 spectra at each frequency step (total 2501 steps)
  - Resonant frequency and coupling coefficient are tuned to be |δf| < 500 Hz and β = 1.9 ± 0.1

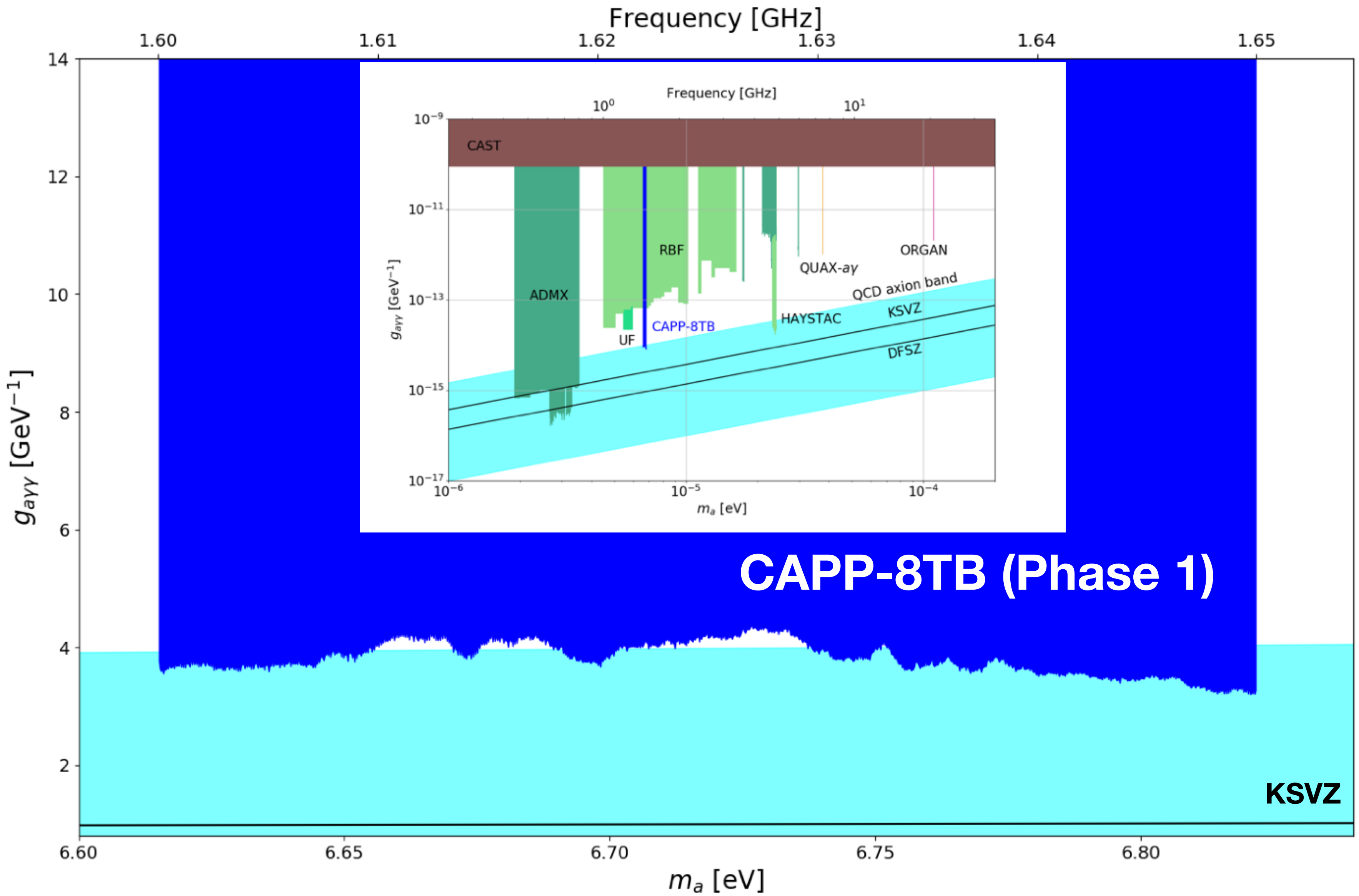






Results

- We exclude the axion-photon coupling ($g_{a\gamma\gamma}$) down to upper QCD axion band over a mass range from **6.62 to 6.82 μeV** (= 1.6 - 1.65 GHz) at a 90% confidence level
  - S. Lee *et al.*, Phys. Rev. Lett. **124**, 101802 (2020)
  - Technical paper is in progress



PHYSICAL REVIEW LETTERS **124,** 101802 (2020)

Axion Dark Matter Search around 6.7 μeV

S. Lee,[1] S. Ahn,[2] J. Choi,[1,†] B. R. Ko,[1,*] and Y. K. Semertzidis[1,2]
[1]*Center for Axion and Precision Physics Research, Institute for Basic Science, Daejeon 34051, Republic of Korea*
[2]*Department of Physics, Korea Advanced Institute of Science and Technology, Daejeon 34141, Republic of Korea*

(Received 14 January 2020; accepted 18 February 2020; published 13 March 2020)

An axion dark matter search with the CAPP-8TB haloscope is reported. Our results are sensitive to axion-photon coupling $g_{a\gamma\gamma}$ down to the QCD axion band over the axion mass range between 6.62 and 6.82 μeV at a 90% confidence level, which is the most sensitive result in the mass range to date.

DOI: 10.1103/PhysRevLett.124.101802

Precision cosmological measurements strongly favor the standard model of big bang cosmology where about 85% of the matter in the Universe is cold dark matter (CDM) [1]. However, CDM itself is beyond the standard model of particle physics (SM), and, accordingly, the nature of about 85% of the matter in the Universe is still unknown to date. One of the most promising CDM candidates is the axion [2], provided its mass is light enough, above 1 μeV [3] and below 3 meV [4]. The axion is the result of the breakdown of a new symmetry which was proposed by Peccei and Quinn [5] to solve the strong *CP* problem in the SM [6]. A consequence of the axion production mechanisms in the early Universe [3,7–9] is that the axion mass range is very broad: the range mentioned above is the optimum for CDM. On the other hand, the open axion mass range can be much broader according to more recent works [10].

The axion haloscope search proposed by Sikivie [11] involves the resonant conversion of axions to photons in a microwave cavity permeated by a static magnetic field. The conversion power corresponding to the axion signal should be enhanced when the axion mass m_a matches the resonant frequency of the resonator mode ν, $m_a = h\nu/c^2$. This makes the axion haloscope one of the most promising methods for axion dark matter searches in the microwave region that approximately fits the CDM region. The resonated power to be detected as the axion signal in SI units is as

$$P_a^{a\gamma\gamma} = g_{a\gamma\gamma}^2 \frac{\rho_a \hbar^2}{m_a^2 c} \omega (2U_M) C Q_L \frac{\beta}{(1+\beta)}, \quad (1)$$

where $g_{a\gamma\gamma}$ is the axion-photon coupling strength. The two most popular benchmark models are the Kim-Shifman-Vainshtein-Zakharov (KSVZ) [12] for axions that couple to beyond the SM heavy quarks, and Dine-Fischler-Srednicki-Zhitnitskii (DFSZ) [13] for axions that couple to the SM quarks and leptons, at tree levels. $\rho_a \approx 0.45$ GeV/cm^3 is the local dark matter density, $\omega = 2\pi\nu$, and $U_M = \frac{1}{2\mu_0} B_{\rm avg}^2 V = \frac{1}{2\mu_0}\int \vec{B}^2 dV$ is energy stored in a magnetic field over the resonator volume V, where $\vec{B}$ is a static magnetic field provided by magnets in the axion haloscopes. The resonator-mode-dependent form factor C whose general definition can be found in Ref. [14] and loaded quality factor $Q_L = Q/(1+\beta)$ are also shown in Eq. (1), where Q is the unloaded quality factor of the resonator mode and β denotes the resonator mode coupling to the load. Assuming the axions have an isothermal distribution, the signal power given in Eq. (1) would then distribute over a boosted Maxwellian shape with an axion rms velocity of about 270 km/s and the Earth rms velocity of 230 km/s with respect to the galaxy frame [15], respectively, which is the model adopted in this Letter.

Here, we report an axion dark matter search with the CAPP-8TB haloscope at the Institute for Basic Science (IBS) Center for Axion and Precision Physics Research (CAPP) [16]. The 8TB stands for our solenoid specifications, the central magnetic field of 8 T and the relatively Big bore of 165 mm.

The CAPP-8TB haloscope has a tunable copper cylindrical cavity as a resonator, a cryogen-free NbTi superconductor solenoid [17], and a typical heterodyne receiver chain equipped with a state-of-the-art high-electron-mobility transistor (HEMT) LNF-LNC0.6_2A [18] as the first amplifier. The experiment maintains the physical temperature of the cavity at about 47 mK using a cryogen-free dilution refrigerator BF-LD400 [19]. The details of the CAPP-8TB apparatus will be discussed in the coming publication [20]. Here we provide an overview shown in Fig. 1.

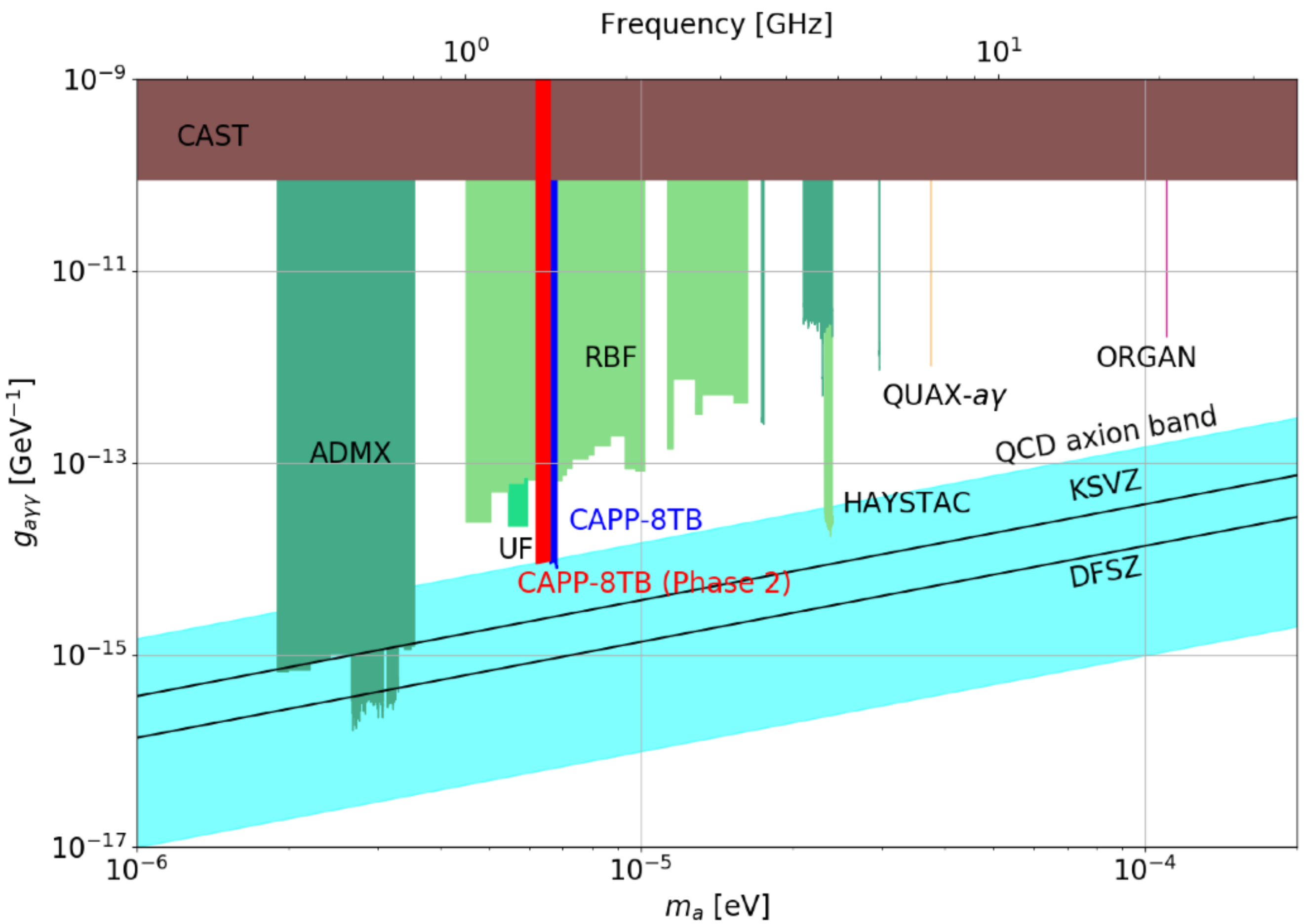
Our cavity is a 3.47 L copper cylinder whose inner diameter and height are 134 and 246 mm, respectively. The frequency tuning mechanism is comprised of a fully alumina based tuning rod system, a locomotive shaft to link the tuning rod axle, and a rotational stepper motor. The motor is

0031-9007/20/124(10)/101802(5) 101802-1 Published by the American Physical Society

*S. Lee et al., Phys. Rev. Lett. **124**, 101802 (2020)*

Prospects

- CAPP-8TB Phase 2 (in preparation)
  - Expanding to the mass range of **6.20 - 6.62 μeV** (= 1.5 - 1.6 GHz) with the same sensitivity (=QCD axion band)
  - (3 + α) months operation is expected
- Possible enhancements in future
  - Quantum limit noise devices → Decreasing T_N dramatically (O(100) mK)
  - Fast DAQ with a digitizer → Increasing DAQ efficiency (η > 90%)



Conclusions

- IBS/CAPP runs several axion search experiments in parallel
  - CAPP-8TB is one of them
- CAPP-8TB is designed to search 5.91 - 7.03 μeV (= 1.43 - 1.7 GHz)
  - Microwave resonant cavity at 50 mK under 8 T
  - Resonant frequency and coupling tuning is implemented
  - High gain (~133 dB) with a low noise temperature (~0.9 K)
  - System is capable to search down to 1.4 × KSVZ
- In phase 1, we excluded upper QCD axion band over 6.62 - 6.82 μeV (= 1.6 - 1.65 GHz) at a 90% C. L.
- Phase 2 is in preparation to scan 6.20 - 6.62 μeV (= 1.5 - 1.6 GHz) with the same sensitivity